SATELLITE-TRACKING AND EARTH DYNAMICS RESEARCH PROGRAMS

Grant Number NGR 09-015-002

Semiannual Progress Report No. 43

1 July to 31 December 1980

Prepared for

National Aeronautics and Space Administration
Washington, D.C. 20546

February 1981

(NASA-CR-163977) SATELLITE-TRACKING AND EARTH DYNAMICS RESEARCH PROGRAMS Semiannual Progress Report, 1 Jul. - 31 Dec. 1980 (Smithsonian Astrophysical Observatory) 101 p HC A06/MF A01 CSCL 08G G3/46

N81-17649

Unclas
41445

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
and the Harvard College Observatory
are members of the
Center for Astrophysics

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investigations, including studies of crustal dynamics, and earth and ocean tides, and for the general development of precision orbit determination. The network performed regular tracking of several other retroreflector satellites including GEOS-1, GEOS-3, BE-C, and Starlette for refined determinations of station coordinates and earth's gravity field and for studies of solid earth dynamics.

A major program in laser upgrading was initiated during this period to improve ranging accuracy and data yield. This program included 1) an increase in pulse repetition rate from 8 ppm to 30 ppm, 2) a reduction in laser pulse width from 6 nsec to 2-3 nsec, 3) improvements in the photoreceiver and the electronics to improve daylight ranging, and 4) an analog pulse detection system to improve range noise and accuracy.

Tests were begun at Mt. Hopkins on three candidate analog pulse detection systems to replace the waveform digitizers (WD2000). The major impetus for the analog system is the speedup in data rate, which could not be accommodated with the digitizer and the increased difficulty in maintaining the complex digitizer equipment. The analog system will also offer potential for improved range noise and accuracy. A design was completed for the modifications to the photoreceiver for the narrow band filter and a more flexible arrangement for the PMT Mounting. A new PMT and PMT base were also selected.

During the reporting period, work continued on the replacement for the bi-planar photodiode currently being used in the laser system start channel. The PIN diode should give a faster, more stable response (less pulse distortion) and less jitter in the system start circuit.

In May, a visit was made to Bangalore, India, to discuss the relocation of the Mt. Hopkins laser system with officials of the Indian Space Research Organization (ISRO). There appears to be agreement on locating the laser at Naini Tal; however, the response from ISRO has been very slow. An updated draft Memorandum of Understanding was sent to ISRO from SAO. We still are awaiting their response. In November the NASA Administration discussed the Laser Program with ISRO while he was in Bangalore. Dr. Dhawan agreed to provide a response in early CY 1981.

2. OPERATING STATUS

The SAO laser sites in Natal, Arequipa, and Orroral Valley continued routine operations throughout the six-month period. Together with the cooperating stations in Wettzell, Shanghai, Dionysos, Grasse, Kootwijk, Helwan, Metsahovi, and Dodaira (see Section 3.), the laser stations obtained a total of 56,282 observations on 3,341 passes of GEOS 1, GEOS 3, BE-C, Starlette, and LAGEOS. These statistics are quick-look passes and points and represent only a percentage of the actual data taken. Monthly statistics of the passes and points, by station and by satellite, are given in Table 1; these data have been sent to the National Space Science Data Center at Goddard Space Flight Center (GSFC). Table 2 shows the 1980 final data processed to date.

The Mt. Hopkins site was closed for regular data taking during the reporting period. The station remains prepared to provide tracking support for brief periods, if requested, but current activities are concentrated on upgrading, documentation, and preparation for relocation.

We continue to maintain the operations reporting procedures requested by NASA by providing statistics of tracking success, weather, and maintenance on a monthly basis. Table 3 gives the six-month summary of this information.

Table 1.

Quick-look passes and points, 1 July through 31 December 1980

Station	July		August		September		October		November		December		Total	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
Arequipa	247	3,252	352	5,025	302	4,462	199	2,570	211	2,716	161	2,006	1,472	20,031
Natal	60	674	147	2,340	85	1,765	125	2,665	137	1,881	82	948	636	10,273
Orroral Valley	128	1,485	161	3,384	164	4,654	148	4,068	78	1,786	64	1,082	743	16,459
Helwan	-	-	-	-	-	-	7	65	1	6	1	29	9	100
Metsahovi	-	-	8	100	11	181	16	338	19	314	7	102	61	1,035
Borowiec	-	-	-	-	-	-	-	-	-	-	-	-	-	-
San Fernando	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kootwijk	2	24	49	624	66	967	2	58	-	-	-	-	119	1,673
Wettzell	3	140	9	404	13	536	17	598	1	21	-	-	43	1,699
Grasse	-	-	30	431	28	428	41	1,528	-	-	-	-	99	2,387
Dodaira	-	-	-	-	-	-	-	-	-	-	1	7	1	7
Dionysis	10	42	73	1,188	34	594	37	763	-	-	-	-	154	2,587
Shanghai	-	-	-	-	-	-	4	31	-	-	-	-	4	31
TOTAL	450	5,617	829	13,496	703	13,587	596	12,684	447	6,724	316	4,174	3,341	56,282

Satellite	July		August		September		October		November		December		Total	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
BE-C	69	874	124	1,666	80	1,148	68	1,215	52	653	36	376	429	5,932
GEOS 1	89	1,067	151	2,301	141	2,698	126	2,414	98	1,438	63	656	668	10,574
Starlette	115	1,519	220	3,379	198	3,795	132	3,057	75	857	79	998	819	13,605
GEOS 3	96	1,224	190	3,329	172	3,316	157	3,088	133	1,918	75	864	823	13,739
Lageos	81	933	144	2,821	112	2,630	113	2,910	89	1,858	63	1,280	602	12,432
TOTAL	450	5,617	829	13,496	703	13,587	596	12,684	447	6,724	316	4,174	3,341	5,282

Table 2.

Final Data Statistics
June-November 1980 Passes/Points

	BE-C		GEOS-1		STARLETTE		GEOS-3		LAGEOS		TOTAL	
	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points	Passes	Points
Orroral Valley	-	-	185	12,423	191	7,935	152	6,219	267	25,628	795	52,205
Natal	87	1,861	155	5,623	114	2,979	169	5,147	36	818	561	16,628
Arequipa	304	9,803	349	16,738	310	12,456	394	16,907	205	10,810	1,562	68,714
TOTAL	391	11,664	689	36,984	615	23,370	715	28,273	508	37,25[illegible]	2,918	137,547

Table 3.

Laser operations summary, 1 July through 31 December 1980.

Station	Passes scheduled	Passes supported	Data obtained*	Passes cancelled owing to weather**	Passes cancelled owing to system down	Passes cancelled owing to other
Natal	2,136 (100%)	1,138 (53%)	632 (44%)	689 (32%)	295 (14%)	14 (1%)
Arequipa	2,577 (100%)	1,911 (74%)	1,449 (71%)	527 (21%)	129 (5%)	10 (0%)
Orroral Valley	2,101 (100%)	838 (40%)	739 (82%)	1,205 (57%)	47 (2%)	11 (1%)

* Number of passes and percent of total scheduled minus passes canceled because of weather.

** Not included are passes attempted but unsuccessful because of poor weather.

3. LASER OPERATIONS AT COOPERATING AGENCIES

In addition to operating its own stations, SAO supports the operation of overseas cooperating laser stations by furnishing orbital elements for predictions, screening quick-look data, and acting as a general U.S. interface. These cooperating agencies are located in Greece, Japan, Spain, The Netherlands, France, West Germany, Egypt, Poland, and Finland. During the past six months, SAO actively supported the Centre National d'Etudes Spatiales (CNES) Starlette program with routine laser tracking, providing CNES with orbital elements to sustain its tracking operation.

The Delft University of Technology's laser system in Kootwijk, The Netherlands, obtained large amounts of tracking data on retroreflector satellites throughout the past six months. For this effort, SAO supplies orbital elements for laser predictions, provides routine processing of quick-look data, helps coordinate operational activities, and routinely screens the data. The laser has been operating at an estimated accuracy of 15 cm, with additional upgrading being planned.

The laser system operated under the cooperative laser tracking program, begun in 1977, with the Soviet Academy of Science, the Technical University of Prague, Czechoslovakia, the Helwan Observatory in Egypt, and SAO, continued to provide data for research programs early in the reporting period. For this program, the Soviet Union and the Czechoslovakians provide and maintain the laser tracking system at Helwan, the Helwan Observatory furnishes personnel to operate the system, and SAO supplies technical consultation, a station clock, and partial operating support from PL 480 funds (Smithsonian Institution Foreign Currency Program). SAO routinely screens and validates

the data. During the last year, the system was upgraded with a new short-pulse laser, improved software, and more rugged optics. The improved range accuracy is estimated to be about 25 cm.

The laser site in Borowiec, Poland, was not operational during this reporting period. This station was also operated under partial support from the Smithsonain Institution Foreign Currency Program.

The station in Dionysos, Greece, owned by the National Technical University (NTU), was not operational as it is still undergoing an upgrading program for improved ranging capability. This system should be back in operation in July in preparation for the MERIT Campaign.

SAO also has close working arrangements with the Institut fur Angewandte Geodasie (IFAG) in the Federal Republic of Germany. The IFAG satellite-ranging system in Wettzell has been tracking LAGEOS and other laser retroreflector satellites with its short-pulse neodymium Yag mode-locked laser system which has consistently demonstrated range-noise performance of 2 to 4 cm. The station operated during January, February and early March.

A new site in Metsahovi, Finland, began sending data during this reporting period. The tracking system uses a 25-nanosecond Q-switched laser pulse with an estimated accuracy of 1 meter.

4. SATELLITE OBSERVING CAMPAIGNS

The laser tracking network continued its program of data acquisition, with particular emphasis on tracking support for LAGEOS for the preliminary MERIT Campaign. In addition, satellite observations were made to:

A. Support the scientific and orbital maintenance requirements for LAGEOS and the Laser Earth Dynamics Project.

B. Support the study of earth body and ocean tides, seasonal and other variations in the earth's gravity field, and the investigation of polar motion.

C. Provide data for improving the accuracy of station coordinates and the gravity-field model, which are necessary for LAGEOS and other geophysics programs.

D. Support the tracking campaign for Starlette in conjunction with CNES.

The practical and scientific importance of the monitoring of the rotation of the Earth has long been recognized. The International Latitude Service was established in 1895 to study polar motion (i.e., the motion of the axis of rotation with respect to an axis "fixed" in the Earth), and has been succeeded by the International Polar Motion Service, now based in Japan. The Bureau International de l'Heure was established in 1911 to provide an international time-scale based on the rotation of the Earth, and today it is responsible for the international scales of atomic time and of universal time, and hence for the basic data on the variations in the rate of rotation of the Earth. An accurate knowledge of universal time and polar motion is required for practical purposes, such as geodetic surveying and precise navigation, but it is also of great scientific value since it provides information about the interior of the Earth and geophysical phenomena that cannot be obtained in other ways; this information could itself be of practical application in the studies of earthquakes and climatic variability.

At present, the international services rely almost entirely on data provided by a network of cooperating observatories using optical instruments such as zenith telescopes and astrolabes. New techniques, such as laser ranging and radio interferometry, promise to provide an order of magnitude improvement in the precision of the data, but (apart from polar-motion data obtained from the doppler tracking of active satellites) there have been no international arrangements for regular observations, nor for the collection and analysis of the data, nor for the speedy and regular publication of results.

MERIT is a program sponsored by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) for a special period of international

collaboration in the Monitoring of Earth-Rotation and in the Intercomparison of the Techniques of observation and analysis. The objectives of the project are: (1) to foster the development of new techniques for the measurement of the variations in the rate and axis of rotation of the earth, (2) to obtain precise data on Earth rotation in order to increase our understanding of the causes and effects of the variations, and (3) to make recommendations on the observational basis and organizational arrangements for future international services on Earth rotation. The program is focussed primarily on LAGEOS for the measurements of polar motion and earth rotation, with Starlette and GEOS-3 being tracked at lower priority for other investigations in geophysics and orbital analysis.

The full proposed program of activities includes (1) initial short periods of observation (during 1980) to test the techniques and improve the arrangements for international cooperation; (2) a later common period (at least a year 1983/84) of regular observation by all suitable techniques; and (3) periods of planning, data analysis, and review. The program relies on the support of observatories, data analysis centers, and international organizations to ensure useful scientific results and a sound basis for the future development of the international services on Earth rotation.

SAO has participated in MERIT in two ways. First, as a data center SAO has provided predictions, status reports, and collected observations for the Satellite Tracking Laser Systems. Second, as an analysis center SAO has used the quick look data received each week, and calculated the position of the earth's pole and the Length of Day (LOD). These data are supplied weekly to the Central Coordinating Center at the Bureau International de l'Heure (BIH). At present SAO is the only new group to provide

these data routinely in an operational way.

The accuracy of the SAO pole position and LOD is hard to assess since there is, at present, no suitable standard of comparison. We believe it to be an improvement over classical data.

To prepare for the three-month Preliminary MERIT campaign, SAO began routinely determining polar motion from Quick Look Data from January 1980. We now have almost one year of data. As a byproduct, we have established the coordinates of many new Laser stations which participated. During this period alone, 20 laser stations provided data, giving one of the richest data sets ever obtained. These coordinates seem to be known with an accuracy of several decimeters, and continued refinement of these coordinates during the next few years may also result in measurement of relative motion of the observating stations, as well as the motion of the whole earth in space.

From the success of the MERIT campaign and examination of this year's data from SAO, both BIH and the U.S. Naval Observatory are planning to use the SAO polar motion and earth rotation data in the officially adopted data. SAO intends to continue this Quick Service and may be a part of the new time and pole position service sanctioned by the International Unions. If so, this would be the first of the new space techniques that will have been incorporated into the classical astronomical services.

Even aside from MERIT, the major emphasis of the SAO program has been and will continue to be on LAGEOS, with the focus on maximizing data yield and accuracy.

LAGEOS serves as a stable reference platform for observations in support of many investigations, including 1) the relative movement and deformation of the earth's tectonic plates, 2) variations in the motion of the earth's polar axis and rotation, 3) improved geodetic and astronomical reference systems, 4) solid-earth and ocean tides, and 5) satellite orbital perturbations.

SAO, GSFC, the University of Texas and several other organizations are using LAGEOS data to develop new analytical techniques for improved baseline measurements and earth-dynamics investigations. In particular, translocation techniques combining long-arc and overlapping observations from station pairs and other combinations of dynamic and geometric techniques offer promise of reaching the centimeter accuracies required to observe crustal motion.

SAO lasers continued to track LAGEOS both for orbital maintenance and for geophysical and orbital analysis at SAO, GSFC, and other research organizations. With installation of the pulse choppers, the SAO lasers are now ranging to LAGEOS with an estimated systematic accuracy about 10 cm (see Section 8). Returns are in the range of 1 to 10 photoelectrons, however, and shot-to-shot range noise is typically 30-50 cm owing primarily to photon quantization and sampling errors. To improve the quality of the data, SAO continues to examine all systematic influences at these low signal strengths and to tighten the screening procedures. During this reporting period, a program of laser upgrading has been undertaken to improve data accuracy and yield on LAGEOS (See Section II).

A summary of the network's tracking activity on LAGEOS during the reporting period is included in Table 4.

Table 4.
Quick-look LAGEOS passes
1 July through 31 December 1980

Station	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Arequipa	247	352	302	199	211	161	1,472
Natal	60	147	85	125	137	82	636
Orroral Valley	128	161	164	148	78	64	743
Total	435	660	551	472	426	307	2,851

5. ENGINEERING

The Engineering Group of the Experimental Geophysics Department provides the daily hardware and systems support necessary to maintain routine network operations. It is also responsible for the system modifications and improvements required for new programs.

5.1 Laser and Photoreceiver

The coatings of the primary and secondary mirrors in the Natal site photoreceiver had deteriorated significantly in the past years of operation because of ambient salt air exposure. The opportunity was taken to strip, recoat and install the mirrors from the Mt. Hopkins photoreceiver into the Natal system resulting in an improved signal strength of approximately 3. The mirrors of the Natal system were in turn refurbished and installed in the Mt. Hopkins system. At that time the Mt. Hopkins photoreceiver was also upgraded to eliminate mechanical instabilities in its field-stop and flip-mirror mechanisms that had been problem sources since its prototype days.

As a part of the laser upgrading program (see Section 10) a redesign of the photoreceiver has been developed to incorporate a 3 Angstrom filter and a PMT shutter. This new design will enable the instrument to accommodate different PM tubes of varying photocathode sizes. The components needed for the modification will be purchased in early CY 1981. As a part of this upgrading program tests are underway to choose a better PMT and PMT base to reduce pulse distortion and range abasing error.

A new cooling unit purchased for the Mt. Hopkins laser was integrated and field tested at that site, making that system more reliable in future operation.

In order to improve the lifetime of optical components in the laser transmitter, new calorimeters were purchased to assist in system calibration. These units were tested and found to be unstable while also producing apparent low readings. The instability problem was cured by replacing some marginal components but the question of low readings awaits further study. We expect to test the calorimeters again in the near future with a ruby laser in the Center for Astrophysics Shock Tube Lab as soon as that system becomes available to us.

Since the introduction of the pulse choppers, it has been noticed that the laser start pulse is subject to noise and pulse-to-pulse variation. The noise source was found to be Pockels Cell switching which is picked up by the coaxial lines of the detector. The pulse variation has been attributed to pick-up in the detector and its pulse forming circuitry. To address these problems, we plan to cover the Pockel's cells with RF shields for the cells, double shielde the coax lines, and replace the current planar photodiodes with PIN diode detectors. Several versions of PIN diode detectors were tested and evaluated. To utilize these detectors, fast pulse amplifiers were purchased to increase the low output of the diodes to the needed voltage levels. Acceptance testing of the amplifiers showed them to be out of specification and they were returned to the manufacturer for repair.

Studies to increase the laser transmitter repetition rate to 30 ppm have been completed. A vendor, Laser Industries, has been selected to furnish the components required for modifications to

the laser power supply. See Section 10 for more detail.

5.2 Pulse Processing

Efforts have continued to reduce the jitter in the return circuit pulse processor electronics and to construct an analog detection system to replace the WD2000 waveform digitizer. The analog detector would enable us to simplify the system electronics and is a fundamental step in the speed up of the laser repetition rate (see Section 10).

Prototypes of three different analog detectors were built and tested in Cambridge with promising results. The prototype systems include: a system based on constant fraction discriminators, a distributed delay line system with amplitudes summed and differenced to measure center of area, and a combination of matched gaussian filter/pulse differentiator and a cross-over dectector. Testing of these devices has now moved on to Mt. Hopkins.

5.3 Minicomputers

Each of the SAO laser field stations has a minicomputer system that performs system calibrations, ranging operation, and other auxiliary functions. Magnetic tape (Linc tape) is the primary storage medium for programs and data. Operator interaction with the computer is through a keyboard/printer (Miniterm) and a CRT display.

The minicomputers and associated peripheral devices in Natal, Arequipa, and Orroral Valley continue to function normally. The system at Mt. Hopkins remains operational.

All field minicomputers remained operational during this reporting period. A set of Linc Drives was received from Peru for repair but that system remained operational with a spare set of drives. Repair work on the faulty drives is underway.

In addition to the field minicomputers, we maintain four similar units in Cambridge. System A is used to post-process field station Linc tape data, which is then stored on industry-compatible magnetic tape for subsequent transfer as input records to the VAX 11/780 central computer. System B is used in the development and testing of software for the field systems. System C serves as the testing mainframe and as a back-up in case of failures in one of the other systems. The fourth system is utilized routinely by personnel in the Communications division.

Because of continued failures experienced on system B, system C was rewired to replace system B in order to more fully investigate this problem. A major failure occurred on system A which caused the loss of many disc files. The problem was isolated and corrected, but work continues on file recovery.

The communications minicomputer continues to assist communications personnel in the preparation, storage, and archiving of data messages. Since the implementation of the data links, laser data have been routinely transfered to and from the VAX with a high degree of reliability. This computer is equipped with Linc-tape units, a keyboard/printer, a paper tape reader and perforator, and a Lexiscope display. The mainframe and all

peripherals have been operating routinely for the last six-month period.

A nine-track tape drive for one of the Cambridge based minicomputers has been received. This device, once interfaced, will eliminate a large part of the formatting and data transfer problems that are now experienced with the seven-track drive.

Studies continue on the feasibility of utilizing a minicomputer-radio link-minicomputer communications path as well as further automation of the the Communications Center. These studies are aimed at increasing current system flexibility and reliability as well as accommodating any further expansion.

5.4 Timekeeping

During the last half of 1980, timekeeping systems for the SAO tracking network have maintained epoch time traceable to UTC (U.S. Naval Observatory) with an accuracy of better than plus or minus 3 microseconds, except for Australia, which maintained +/-5 microseconds from July 1st through July 22nd, and Egypt, which maintains time to plus or minus 50 microseconds. Each SAO tracking site is equipped with a broad-based timing system comprised of dual parallel timing channels. Cesium oscillators, backed up by rubidium oscillators, offer a stable time base for each channel. Redundant time accumulators guard against time discontinuities, and redundant VLF/OMEGA receivers provide a reliable backup and frequency reference for the system. Without NTS epoch data, portable clock comparisons are required to provide the necessary epoch reference checks until another satellite-based time transfer system, such as GPS or Transit, can be implemented. Table 5 summarizes the network accuracy.

All laser sites have had portable clock comparisons during this period, with the exception of Egypt. Table 5 summarizes the results of these comparisons.

The U.S. Coast Guard loaned SAO a portable cesium clock for comparisons at South American tracking stations, to prepare for the MERIT tracking campaign. Both the Natal and the Arequipa comparisons made in September tracked to the last comparisons made in June, 1978. Traceability was better than +/-4 microseconds for Natal. The accuracy of the portable clock set was better than 0.4 microseconds. An earlier attempt at a portable clock trip in July failed because the power supply/charger developed problems and only a one way comparison with the Observatorio Nacional in Rio de Janeiro could be made. Repairs and tests were made by the manufacturer and at SAO before the successful trip was completed in September.

A portable clock trip to Orroral Valley during September helped explain epoch time differences during the June thru August period. Cesium replacements at the NASA Minitrack site during June and August caused some unexplained differences of up to 28 microseconds between Australian National Mapping and NASA timing data. SAO derives its epoch reference from the minitrack site.

A portable clock comparison was made between the Mt. Hopkins timing system and one at nearby Fort Huachuca, Arizona. Accurate time was necessary at the tracking site because of electronic systems tests to be performed starting in December.

New 50 ohm driver boards were installed at both South American sites. Timing system counter measurements have improved with the better noise rejection and crosstalk characteristics of the new boards.

Line 10 TV timing equipment was installed at the Natal site to provide a daily epoch check. These comparisons are made among other sites in Brazil and are coordinated by the Observatorio Nacional in Rio de Janeiro.

Table 5
SAC NETWORK TIMEKEEPING STATUS FOR 1980

Definitions:

(STAT - UTC) epoch range of SAO field station main clock
a positive quantity means station clock ahead of UTC
as maintained by the US Naval observatory (USNO)

REDUCTION UNCERTAINTY estimated absolute error of reduced station
time during the period specified. Future clock comparisons
may lower this uncertainty value.

EPOCH SET UNCERTAINTY estimated epoch time transfer accuracy

STATION	REDUCTION PERIOD from	thru	(STAT - UTC) RANGE microseconds	REDUCTION UNCERTAINTY +/-microseconds	EPOCH SET UNCERTAINTY +/-microseconds	LAST COMPARISON by	when	COMMENTS
AUSTRALIA	Jan 1	Jun 30	8 to 19	5	1	USNO	5 Sept 80	
	Jul 1	Dec 31	-4 to 16	3 to 5				
	except Mar 22		15	18				
	except Apr 15	Apr 16	14 to 18	20				
	except Jun 17		16	10				
	except Jul 15	Jul 16	3 to 16	22				
	except Jul 22		-64628	64630				
BRAZIL	Jan 1	Jun 30	1 to 11	3 to 5	1	SAO/cs	17 Sept 80	
	Jul 1	Dec 31	0 to 11	2 to 3				
	except Apr 10		-4 to 2	341				
EGYPT						SAO/xtal	31 Mar 76	no data received
INDIA				1000	9	SAO/xtal	20 Dec 76	no reduction submitted
JAPAN					20			no data received
MT. HOPKINS					2	SAO/xtal	26 Nov 80	station tests only
PERU	Jan 1	Jun 30	-11 to 1	5 to 7	1	SAO/cs	11 Sept 80	
	Jul 1	Dec 31	-9 to 19	2 to 3				
	except Jun 13		50 to 55	5 to 13				
SPAIN	Jan 1	Apr 11	-43 to 63	10	1	USNO/cs	14 Mar 79	

6. COMMUNICATIONS

The communications center provides voice and teletype radio links to the SAO laser field stations in Arequipa and Natal. SAO also maintains FTS service within the continental United States, and is connected with Western Union, TELEX, AUTODIN, NASCOM and recently acquired RCA GLOBOM circuits for worldwide communications. The RCA GLOBOM circuit has been installed and operating on line since early December. We are presently sending 75-80% of our overseas traffic, formerly passed by the W. U. TELEX, because of the less expensive message rates. W. U. TELEX is retained, however, for domestic use and some overseas traffic.

The HF communication links with Natal and Arequipa have been operating satisfactorily; however, the teletype equipment continually requires adjustments and continues to be the weak link in the system.

The SAO Cambridge radio room has undergone some major changes, including: the removal of the 10kw transmitter and associated power, the installation of a power distribution panel and circuit breakers for the remaining two 1kw transmitters and the receiver rack, the addition of an equipment interface switching panel and associated interface wiring, and the installation of a space HAL ST-6 demodulator/tone keyer. In addition to this, the equipment within the room has been rearranged to allow for more efficient operating procedures, and a new operations manual has been written and is in its final draft. A Bird model 4381 R.F. Power Analyst has been acquired for testing transmitter power at SAO Cambridge.

7. DATA SERVICES AND PROGRAMMING

The Data Services and Programming groups perform central data processing and develop and maintain software for the laser tracking network. The Data Services group focusses on a continuous data exchange with laser sites in the SAO network and with other agencies and organizations both domestic and foreign. It examines raw ranging data, generates ephemerides for all satellites tracked by the network, and deposits the final SAO ranging data in the NSSDC. The Programming group is responsible for software used at all the laser sites in the SAO network, and at the central facility in Cambridge.

7.1 Data Services

Data Services is responsible for two major areas of activity: the quick-look cycle and final data processing. On a weekly schedule, the SAO and cooperating laser stations send small subsets of their acquired quick-look data to Cambridge. These data form the basis for updated orbital elements, which are generated by Data Services and communicated back to the field stations for use in computing the predictions necessary for laser satellite ranging.

The full data sets are recorded on Linc magnetic tape and mailed from the SAO laser stations to Cambridge and sent through the final data-processing cycle. During this phase, data quality is assessed by an engineering filter, and the data are then processed through a noise filter, a time-corrections program, and a formatter, which outputs the data in the NASA coded format as well as the SAO coded format. It is the NASA coded format that is supplied to the NSSDC.

The quick-look functions of the Data Services operation have evolved into a stable, reliable, and smoothly running procedure. Acquisition orbits were computed and transmitted each week virtually without incident. The quality of these orbits remains very high; ephemerides are now routinely computed to the sub-10-meter level and, in the case of LAGEOS, to the 2-meter level.

In the last six months, the Data Services group processed 56,282 laser quick-look data points and handled 3,341 passes from the SAO and cooperating stations on GEOS 1 and 3, Starlette, BE-C, and LAGEOS. (See Table 1).

A highlight of this reporting period was the participation of SAO in the Short MERIT Campaign of international investigations involving the Earth's rotation and pole position. The Data Services group, using Lageos data from the SAO and NASA laser networks as well as from certain cooperating foreign organizations, was able to obtain the earth's pole position as a by-product of the routine orbital determination starting in August, with the beginning of the 3-month MERIT Campaign. These pole positions were transmitted routinely to the B.I.H. in Paris as a rapid service to the world scientific community.

Final data from the SAO laser network for the period March - April 1980 were transmitted to the NSSDC in July. May data were submitted in August, June data in September, and July 1980 through October 1980 data were transmitted in December.

7.2 Programming Support

A small staff of computer programmers supports the operation of the laser tracking program. In addition to regular maintenance and upgrading of the minicomputer and production processing programs, the programmers develop software to meet new needs and support Data Services in routine processing as necessary. This group also analyzes test data for laser system maintenance and for planning laser system modifications to improve performance. The programming staff completed the data control and accounting package for the final data-processing cycle. This package facilitates archiving, control, retrieval and trouble-shooting final data. Basically this software maintains a file that allows the following of individual passes through the various processes, the observation of their status, and the generatation of statistics. This package was completed and placed in use by the Data Service Group.

Our programmers completed work on the zero-set check of the orbit theory used in Cambridge (GRIPE) with that used at the field stations (FLPPS). As noted in earlier reports, this is a full consistency check of quick-look and prediction software. At the present time an average of less than 10-arcsec directional difference and less than one hundred meters range difference between the full and abbreviated orbit packages has been attained. At the moment this level is adequate and the zero set procedure will be performed once a year or whenever changes are made to either package to ensure system integrity.

However, in order to succeed in daylight ranging to LAGEOS it will be necessary to upgrade the orbit software and field predictions to the sub-microsecond level (100m). In this semi-annual reporting period extensive investigation and

numerical testing were performed on the compatibility between the headquarters orbital routines and the field programs. Discrepancies at this interface would be amplified with time over the prediction period. Problem areas that were identified included: 1). a small (10m) bug found in the Keplerian motion. 2). A 100-200m per week discrepancy found in the lunar theory used in the field prediction packages. Updating the field software will require a major programming effort. 3). A 20m problem was found to exist in the tesseral harmonics. The most critical item is the lunar theory incompatibility. A major effort is now being applied to this issue. The other two problems which appear to be software "bugs" are being left in abayence at the moment.

Having identified the major discrepancy as the lunar perturbation theory, it was decided to attempt to incorporate the fully developed integration theroy as used in the precision orbit determination program in the field minicomputer laser pointing software package (FLPPS). The technical problem will likely concern fitting this code into the limited memory available, and work is focussed in this direction at the moment.

The other major area of intense programming effort concerned the laser control program which supplies the laser mount with prediction information on demand and logs the results of laser ranging on magnetic LINC tape for further processing.

Two separate, but related hardware changes are in the works which requiree substantial modification to the Direct Connect package. The first change is the replacement of the WD2000 waveform digitizer with alternative waveform discrimination circuits. Considerable effort was made to develop a version of Direct Connect to properly treat this new data configuration.

Preliminary versions for testing engineering were completed, but it is anticipated that continuing maintenance and modification will be needed.

The second major change is the speed-up of the repetition rate to 30 pps. A stripped down version of Direct Connect was successfully tested in a simulator package (not an actual laser system) at the year's end. The next stages of development of this package will evolve by adding as many features as possible while still accommodating 30ppm. One casualty of this trade-off between processing speed and some initial "on-line" data processing was the second or reduced data file. The output of the Direct Connect program consists of a single LINC tape file, which will be a combination of raw and reduced data.

The Quick-look Data Catalog program was completed this period, along with numerous minor modifications to field minicomputer and headquarters main-frame software.

8. DATA QUALITY

Since the installation of the pulse chopper coupled with improved pulse processing, the SAO laser systems have been operating at an estimated 10 cm accuracy. This higher accuracy, however, must be monitored very carefully to ensure that the system does not degrade and that the ranging capability is maintained. In the following subsections, several key factors and test results associated with the determination of data quality are received Where possible, tests during this reporting period have been used to characterize the system at each station.

8.1 Systematic Errors

We routinely separate the systematic errors of the laser ranging system into three categories: spatial, temporal, and signal-strength variations. Spatial variations refer to differences in time of flight depending on the position of the target within the laser beam. Temporal variations relate to system drift between prepass calibration, satellite ranging, and postpass calibration. Variations in range due to changes in signal strength from pulse to pulse are a function of receiver characteristics and digitizer sampling interval.

Spatial variations. Spatial variations, or the waveform error, were measured at Mt. Hopkins several times. Table 6 gives the results before and after installation of the pulse chopper. The two wavefront measurements performed with the chopper show a maximum deviation of plus or minus 0.3 nsec (4.5 cm) from the mean value across the wavefront. The standard deviation of the excursions is about 0.2 nsec (3 cm).

Table 6. Wavefront distortion.

Date of measurement	Spacing between points (arcmin)	Average number of photoelectrons received	rms wavefront distortion (nsec)	Maximum excursion (nsec)
26 Feb 1974	0.3	88	1.4	3.9
18 March 1974	0.6	56	0.8	2.7
9 Nov 1978	0.3	56	0.19	0.6
1 Dec 1978	0.42	87	0.17	0.6

Temporal variations. Temporal variations are estimated by the difference between prepass and postpass calibration measurements. Recent results from the three operating stations are shown in Figures 1, 2 and 3. These prepass and postpass calibration differences represent an upper bound, since other statistical errors are also included.

Figure 1.

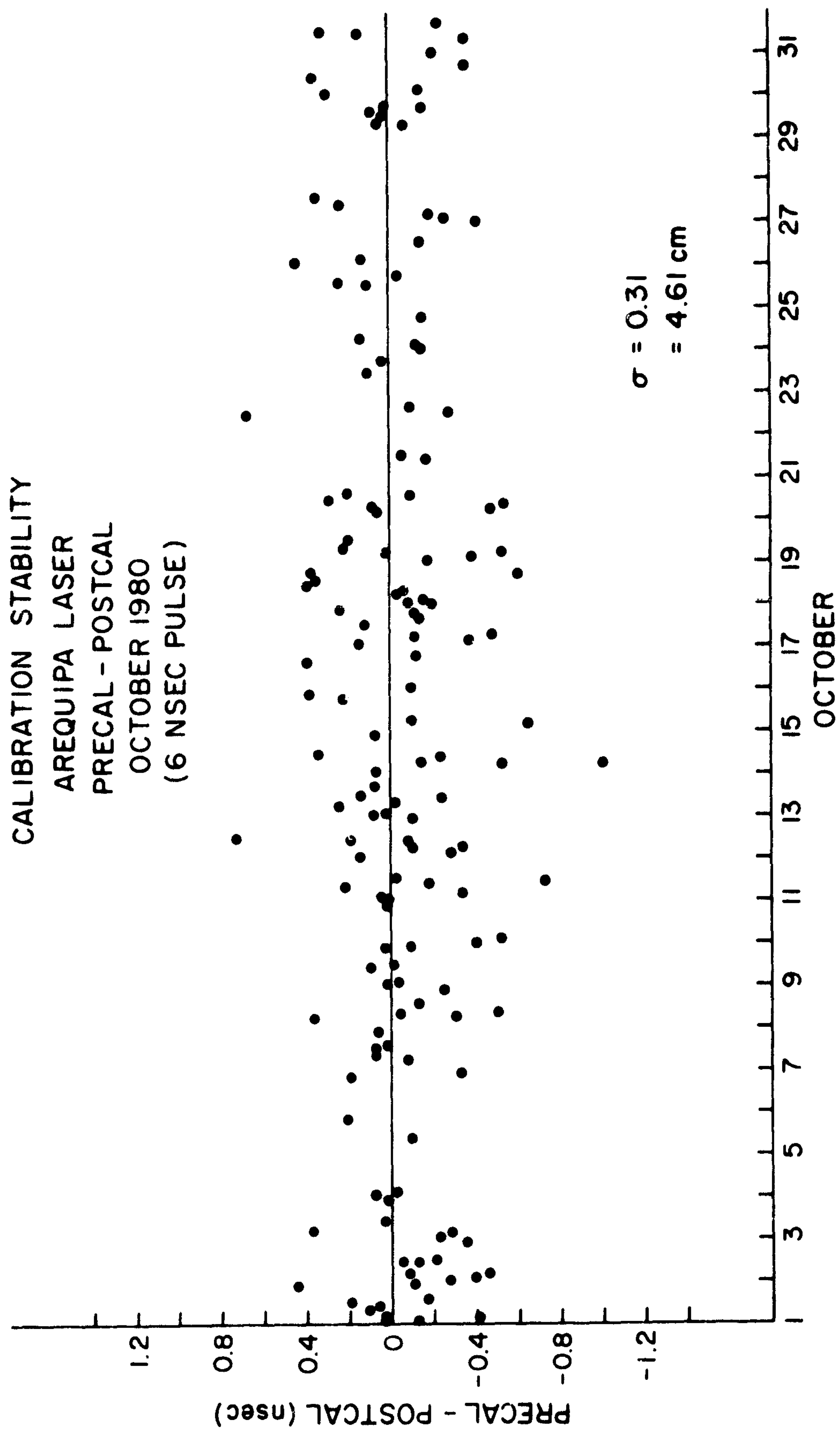

CALIBRATION STABILITY
AREQUIPA LASER
PRECAL - POSTCAL
OCTOBER 1980
(6 NSEC PULSE)
σ = 0.31
= 4.61 cm
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
PRECAL - POSTCAL (nsec)
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
OCTOBER

Figure 2.

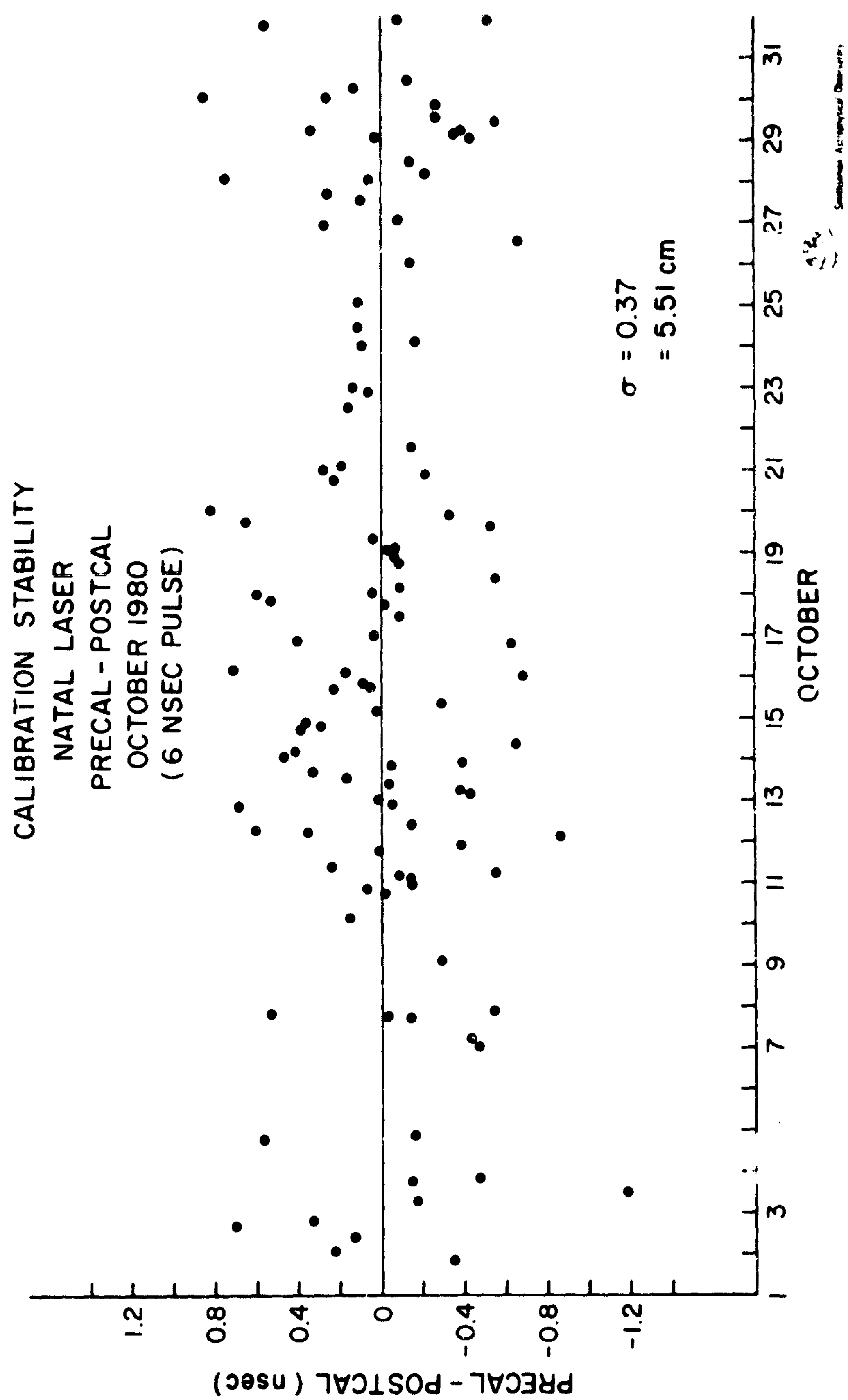
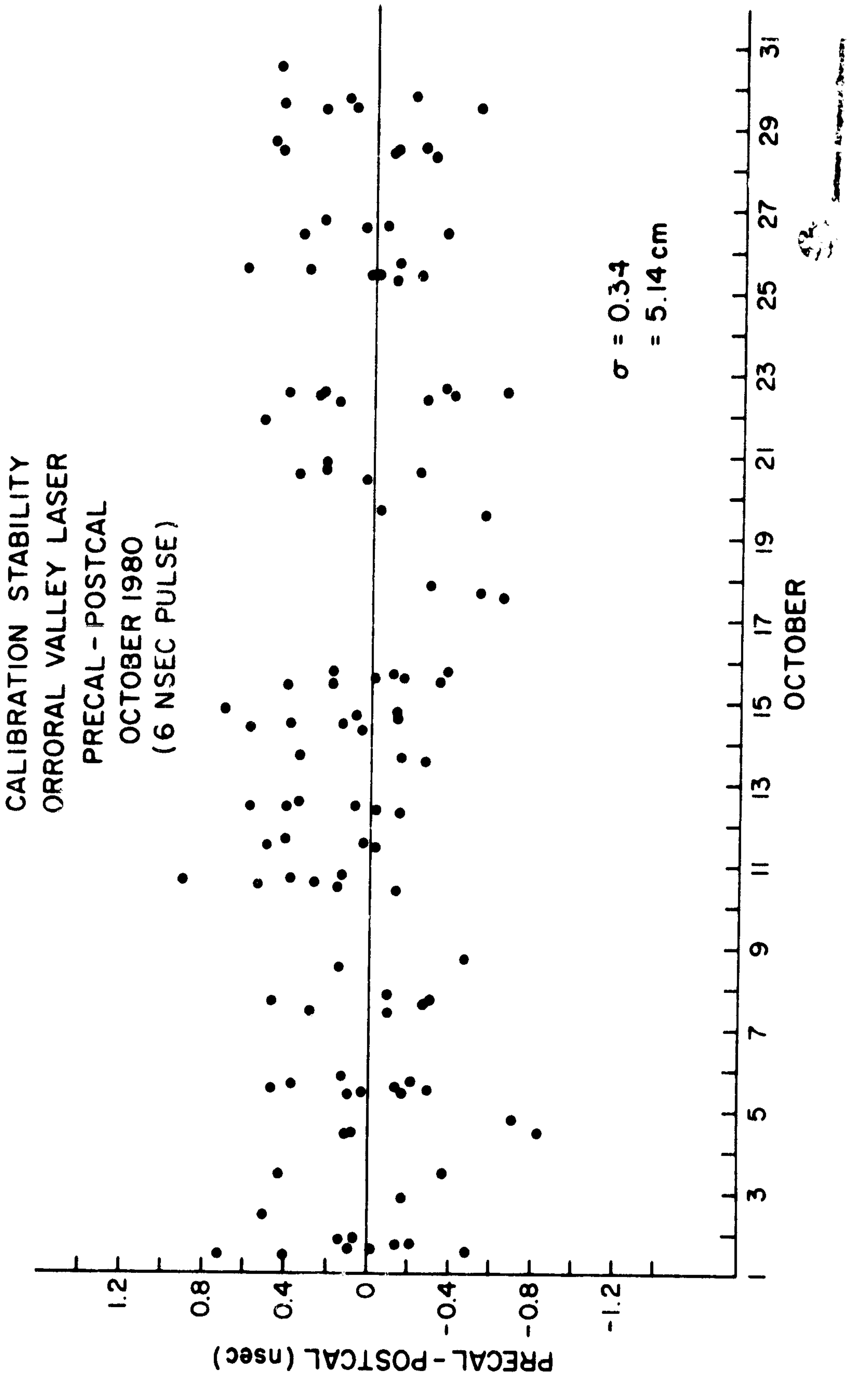
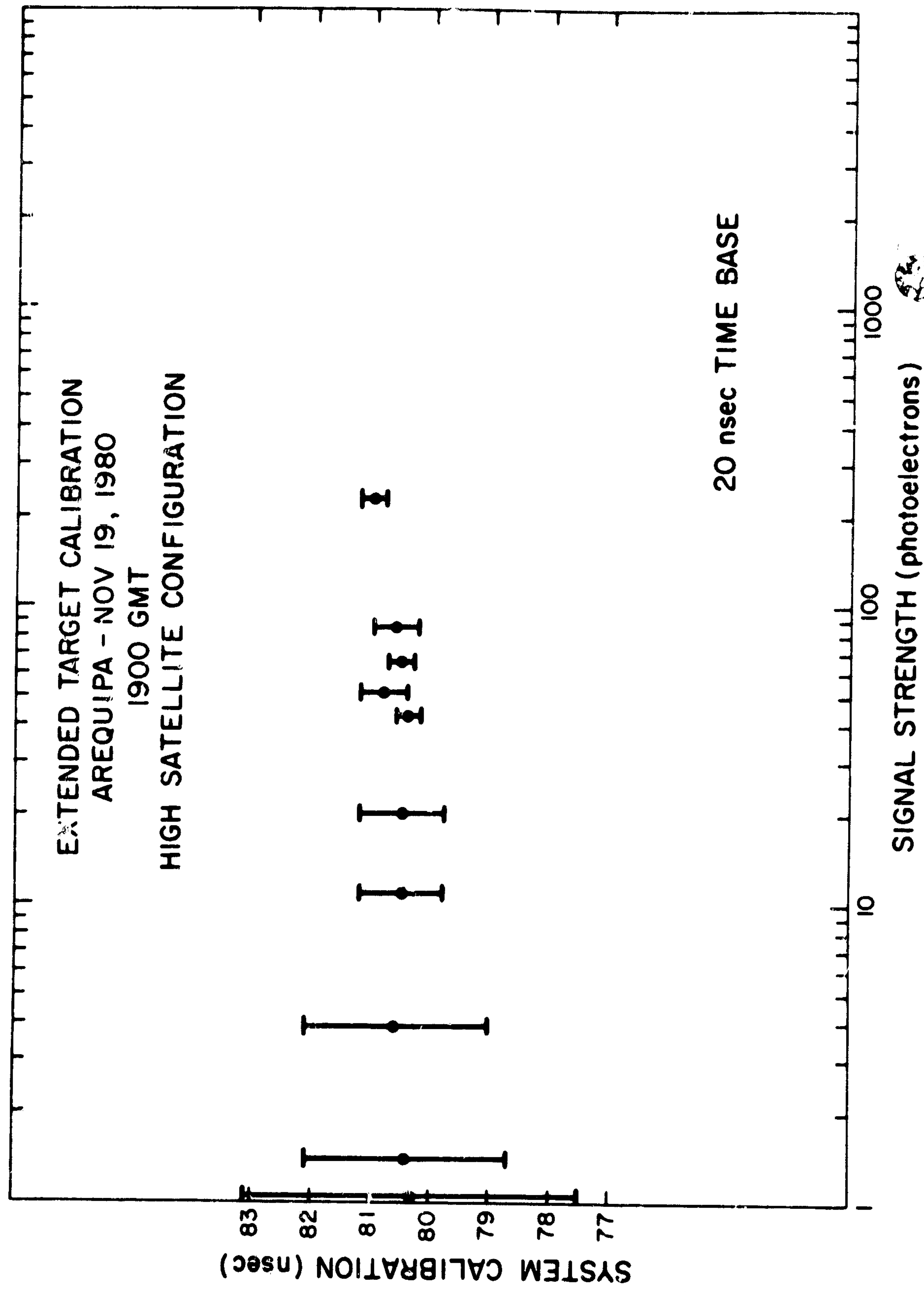

CALIBRATION STABILITY
NATAL LASER
PRECAL - POSTCAL
OCTOBER 1980
(6 NSEC PULSE)
σ = 0.37
= 5.51 cm
PRECAL - POSTCAL (nsec)
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
3
7
9
11
13
15
17
19
21
23
25
27
29
31
OCTOBER

Figure 3.


CALIBRATION STABILITY
ORRORAL VALLEY LASER
PRECAL - POSTCAL
OCTOBER 1980
(6 NSEC PULSE)
σ = 0.34
= 5.14 cm
PRECAL - POSTCAL (nsec)
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
OCTOBER
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31

Signal-strength variations. Variations in apparent range with signal strength have been examined with extended target calibrations over the dynamic range of the laser instrument. Figures 4, 5, and 6 illustrate recent calibration data taken in the high-satellite configuration. On high satellites (LAGEOS), the system is operated right down to the single photoelectron level and the digitizer is operated with a 20-nsec baseline (1-nsec sampling). In this mode of operation, the extended target calibrations typically show a flat response in the 1 to 50 photoelectron region to plus or minus 0.4 nsec (6 cm) or better.

Figure 4.



Smithsonian Astrophysical Observatory

Figure 5.

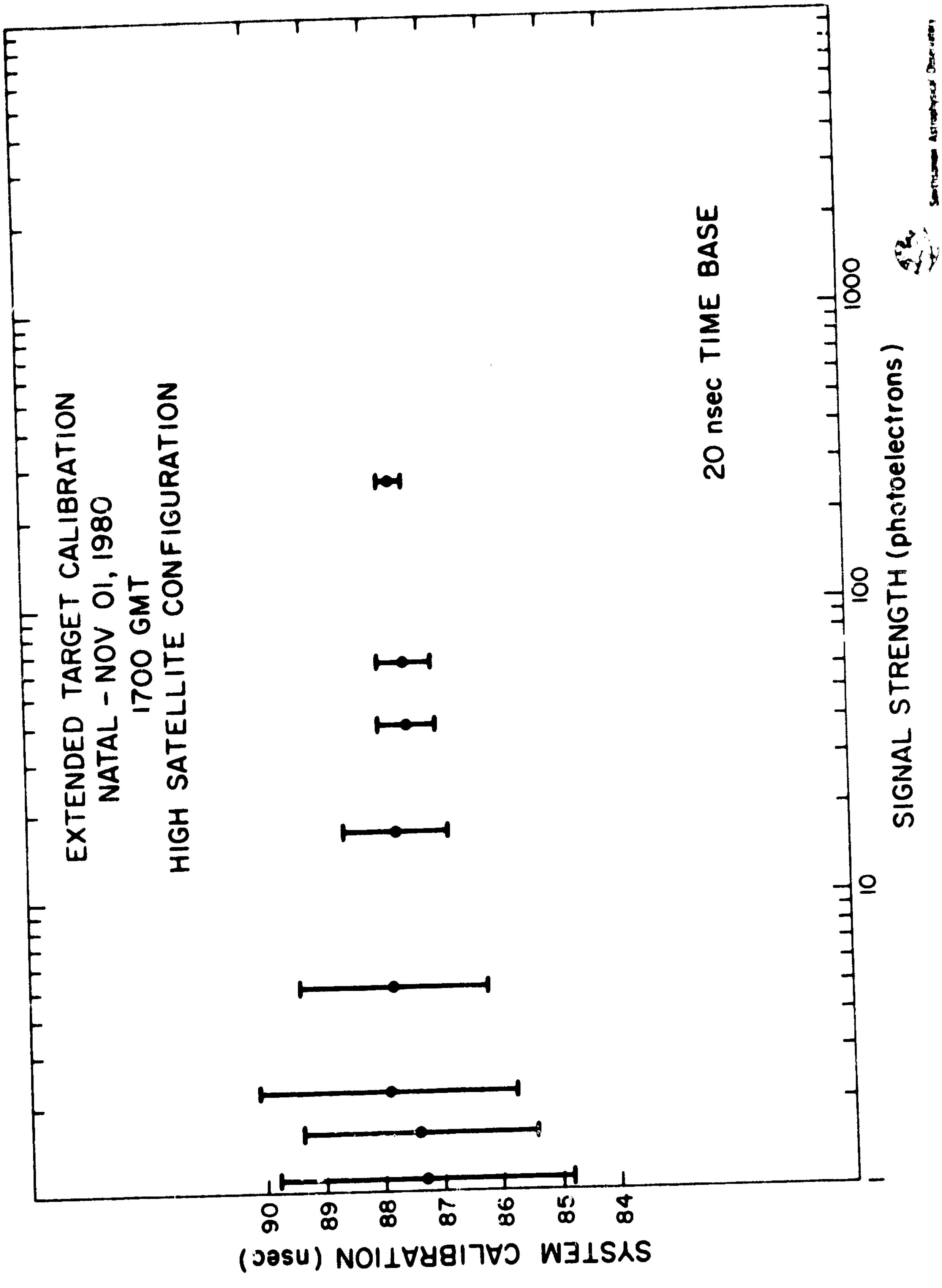
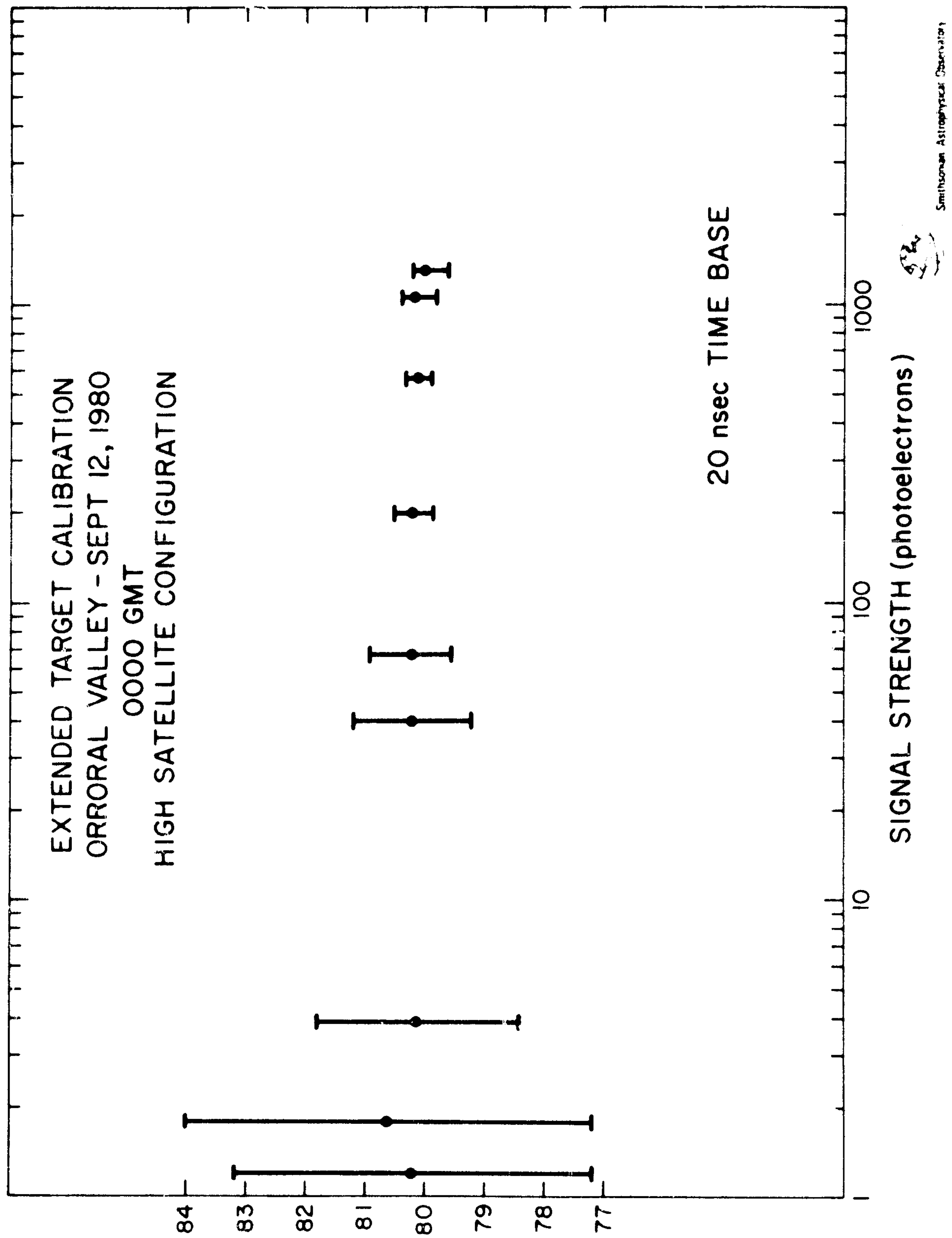

EXTENDED TARGET CALIBRATION
NATAL - NOV 01, 1980
1700 GMT
HIGH SATELLITE CONFIGURATION
20 nsec TIME BASE
SYSTEM CALIBRATION (nsec)
90
89
88
87
86
85
84
SIGNAL STRENGTH (photoelectrons)
10
100
1000
Smithsonian Astrophysical Observatory

Figure 6.


EXTENDED TARGET CALIBRATION
ORRORAL VALLEY - SEPT 12, 1980
0000 GMT
HIGH SATELLITE CONFIGURATION
20 nsec TIME BASE
SYSTEM CALIBRATION (nsec)
84
83
82
81
80
79
78
77
SIGNAL STRENGTH (photoelectrons)
1
10
100
1000
Smithsonian Astrophysical Observatory

Error budget. Using systematic error values of 4.5, 6, and 4.5 cm for spatial, temporal, and signal-strength variations, respectively, for low satellites and assuming that these errors are independent, the root-sum square (rss) error due to systematic sources is less than 9 cm (see Table 7). For the higher satellites, the errors are typically 4.5, 6, and 6 cm, respectively, giving an rss of 9.5 cm. These, then, are the systematic errors that can be expected for data averaged over a pass. In addition, errors in timing, refraction, and spacecraft center-of-mass corrections need to be applied to the data; these errors are basically the same as those in the NASA systems, since essentially the same equipment types are used.

Table 7. Summary of systematic errors.

Source	Low satellites (cm)	High satellites (cm)
Wavefront distortion (spatial)	4.5	4.5
System drift (temporal)	6.0	6.0
Calibration (signal strength)	4.5	6.0
rss	8.7	9.5

8.2 System Noise

The range noise in the SAO lasers is determined in large part by return signal strength. Noise figures are typically in the 10- to 20-cm range for low orbiting satellites. With LAGEOS, at signal strengths of 1- to 5-photoelectrons, noise figures are several times larger (see Table 8). It should be noted that the theoretical random statistics from photoquantization with the 6-nsec chopped pulse are about 30 to 40 cm. This of course is degraded by jitter in the start and stop channel of the system electronics and by the current PMT.

Table 8.
LAGEOS passes from Arequipa, Natal, and Orroral Valley, October 1980.

Date	Station	Pass Stability (Pre-Post Calibration (CM)	RMS (Residual to Polynomial fit) (CM)	Number of Points
10/1	Peru	0.60	28.7	37
10/1	Peru	1.50	38.5	52
10/1	Australia	1.20	30.2	63
10/1	Australia	-2.25	30.1	169
10/2	Peru	-6.75	32.1	90
10/3	Australia	-5.55	24.9	34
10/3	Peru	6.72	44.8	51
10/4	Australia	-12.60	40.1	47
10/5	Australia	0.60	39.3	13
10/5	Australia	-2.25	43.4	98
10/5	Australia	-3.15	37.2	113
10/7	Australia	-4.05	33.2	128
10/7	Australia	4.20	27.9	34
10/7	Peru	-1.20	64.1	7
10/7	Brazil	-7.05	38.9	13
10/8	Australia	2.25	54.3	47
10/8	Peru	5.55	36.9	45
10/10	Australia	13.80	47.9	75
10/10	Australia	2.10	42.0	66
10/11	Australia	0.60	46.0	36
10/11	Peru	-5.25	43.9	42
10/11	Brazil	-2.25	61.2	15

Table 8 (Continued)
LAGEOS passes from Arequipa, Natal, and Orroral Valley, October 1980.

Date	Station	Pass Stability (Pre-Post Calibration (CM)	RMS (Residual to Polynomial fit) (CM)	Number of Points
10/12	Australia	6.00	26.5	63
10/12	Australia	5.55	38.8	74
10/12	Peru	-4.35	45.6	31
10/12	Peru	-5.25	38.2	92
10/13	Australia	-4.05	56.6	62
10/13	Australia	5.25	27.0	176
10/13	Peru	3.60	35.7	11
10/14	Australia	8.85	57.0	18
10/14	Australia	6.00	59.0	52
10/14	Australia	1.05	39.4	111
10/14	Peru	-2.40	59.0	9
10/14	Brazil	7.05	50.0	32
10/15	Australia	-4.05	36.0	22
10/15	Australia	-1.65	45.40	114
10/15	Peru	-9.90	36.5	43
10/16	Brazil	-10.65	34.1	9
10/17	Australia	-8.10	49.9	82
10/17	Peru	-7.20	27.9	63
10/18	Peru	-0.60	38.1	88
10/19	Australia	-0.60	33.4	63
10/20	Australia	0.45	36.1	68
10/20	Australia	-3.45	28.2	147

Table 8 (Continued)

LAGEOS passes from Arequipa, Natal, and Orroral Valley, October 1980.

Date	Station	Pass Stability (Pre-Post Calibration (CM)	RMS (Residual to Polynomial fit) (CM)	Number of Points
10/20	Peru	1.05	31.8	68
10/22	Australia	3.45	28.5	111
10/22	Australia	-5.40	31.5	137
10/24	Brazil	-2.70	45.6	33
10/25	Australia	-0.30	56.4	37
10/25	Australia	9.60	50.0	97
10/26	Australia	-5.55	23.0	12
10/26	Australia	-0.75	39.7	96
10/26	Australia	4.05	65.5	14
10/28	Australia	7.05	52.9	63
10/28	Australia	7.35	38.9	144
10/29	Australia	-7.65	28.4	33
10/29	Australia	6.75	36.5	106
10/29	Australia	-3.00	33.8	125
10/29	Brazil	-4.95	37.3	39
10/30	Australia	7.05	30.2	36
10/30	Peru	-2.40	30.1	46
10/31	Peru	0.00	51.5	78

8.3 Long Arc Analysis

In addition to the system calibration tests and short arc analysis, we also examine the data with a long arc analysis to determine an upper bound on systematic bias. Using a 10-12 day arc, we determine a mean offset for each pass which is the result of instrumentation errors and modelling error due primarily to gravity field and station position. Two such runs during this reporting period are shown in Tables 9 and 10 Most of the pass offsets denoted as <p> are in the neighborhood of 10-20 cm or less, with some examples as large as 50 cm. At the moment this type of behavior is anticipated from the modelling errors above, so the current feeling at both GSFC and SAO is that the ground based measurements are indicative of the ranging accuracy.

Table 9

LAGEOS

Long Arc Analysis

Final Data

September 12-25, 1979

STATION	DATE	HOUR	NO. PTS.	SIGMA	<p>
7907	Sept. 13	01	30	48 cm	9 cm
7907	Sept. 13	23	46	47 cm	- 2 cm
7907	Sept. 14	09	21	48 cm	-53 cm
7907	Sept. 16	10	15	66 cm	-41 cm
7907	Sept. 19	00	34	47 cm	-14 cm
7907	Sept. 19	09	24	42 cm	-13 cm
7907	Sept. 21	23	42	47 cm	5 cm
7907	Sept. 22	08	19	67 cm	- 1 cm
7907	Sept. 24	00	24	51 cm	-11 cm
7907	Sept. 24	23	8	48 cm	4 cm
7943	Sept. 12	10	48	31 cm	- 3 cm
7943	Sept. 15	19	38	55 cm	-11 cm
7943	Sept. 18	09	51	24 cm	-17 cm
7943	Sept. 23	09	35	32 cm	- 6 cm
7943	Sept. 25	19	26	37 cm	30 cm

7907 Arequipa

7943 Orroral Valley

Table 10

LAGEOS
Long Arc Analysis
Final Data
August 4-14, 1979

STATION	DATE	HOUR	NO. PTS.	SIGMA	<p>
7091	Aug. 7	02	29	51 cm	-17 cm
7082	Aug. 7	05	31	27 cm	21 cm
7082	Aug. 10	04	38	6 cm	4 cm
7082	Aug. 11	08	30	30 cm	32 cm
7082	Aug. 14	03	31	14 cm	- 9 cm
7943	Aug. 4	10	42	22 cm	- 4 cm
7943	Aug. 7	10	42	30 cm	3 cm
7943	Aug. 13	08	44	37 cm	6 cm
7943	Aug. 14	20	21	40 cm	5 cm
7907	Aug. 4	03	13	43 cm	1 cm
7907	Aug. 5	01	21	29 cm	- 5 cm
7907	Aug. 8	00	13	45 cm	- 3 cm
7907	Aug. 8	23	12	45 cm	-34 cm
7907	Aug. 11	00	4	18 cm	-21 cm
7907	Aug. 11	23	5	39 cm	- 2 cm
7907	Aug. 13	01	8	39 cm	9 cm
7907	Aug. 13	23	8	33 cm	- 3 cm
7929	Aug. 11	22	12	34 cm	-29 cm

7091 Haystack
7082 Bear Lake
7943 Orroral Valley
7907 Arequipa
7929 Natal

9. RELOCATION OF THE MT. HOPKINS LASER

The NASA Crustal Dynamics project calls for the development of a system of mobile lasers (MOBLAS) to be used in conjunction with lasers already in place to achieve a global network. Early plans included mobile lasers in western Australia, Diego Garcia, Kwajalein, American Samoa, Marcus Island, and Madrid, Spain; the SAO laser sites at Arequipa, Natal, and Orroral Valley; and the University of Hawaii site at Mt. Haleakala. This development plan has since been modified to use the Institut fur Angewandte Geodasie's laser in Wettzell for coverage over Europe, thereby obviating the need for a mobile laser in Madrid, to delete Marcus Island, and to relocate SAO's Mt. Hopkins laser to India, rather than placing a mobile laser at Diego Garcia. This last decision was based on the poor climatic conditions at Diego Garcia, the inability to monitor local deformations there, and the high costs of operating a system on the island.

In our FY 1980 proposal, SAO outlined a program to relocate the Mt. Hopkins laser station to a site in India. The plan was based on a cooperative arrangement with the Indian Space Research Organization (ISRO) at a mutually agreeable site. SAO proposed to provide Excess Currency (PL480) to partially support the operation. ISRO suggested Kavalur, a site near Bangalore where a Soviet laser and camera are presently being maintained. After consideration of logistics, facilities, weather, and location it became evident that Kavalur would not be an adequatre site and SAO proposed that the laser be located at the Uttar Pradesh State Observatory at Naini Tal, a site which has been an SAO Baker-Nunn camera site for over 20 years. The site was deemed acceptable to SAO because of its excellent weather conditions, its established facilities and personnel, and its accessibility in terms of logistics and communications. Earlier concerns about the

degrading effects of local crustal motions on long baseline measurements have been allayed with a plan to use geodetic and geophysical measurements to monitor local crustal movements. A proposal was submitted to the Smithsonian Institution for PL-480 Excess Currency to support part of the expenses to be incurred by SAO, and plans were developed for the required modification of the Baker Nunn building at Naini Tal for laser installation.

ISRO did not provide information on any candidate laser station site other than Kavalur; in mid-February 1980, NASA and SAO agreed that the UPSO site at Naini Tal would be suitable for the laser station and communicated this decision to ISRO and UPSO. A revised MOU based on placing the laser at Naini Tal was drafted by SAO and sent to ISRO for comments. The revised MOU was discussed at a meeting with ISRO at Bangalore, India, in May 1980. It appeared that there was general agreement on the roles that ISRO, UPSO, and SAO would play in the cooperative laser program. It was anticipated that all participants would give final approval by late summer.

Under the arrangements discussed with ISRO, UPSO and the U.S. Embassy, it was anticipated that:

1. ISRO would pay the bulk of the local expenses to be incurred at Naini Tal.

2. SAO through Excess Currency Program (PL 480) would support transportation of goods, travel expenses, local administration, and some communication and other local expenses in India.

3. SAO through NASA funding would pay salaries and some expenses for U.S. employees, plus station support costs normally

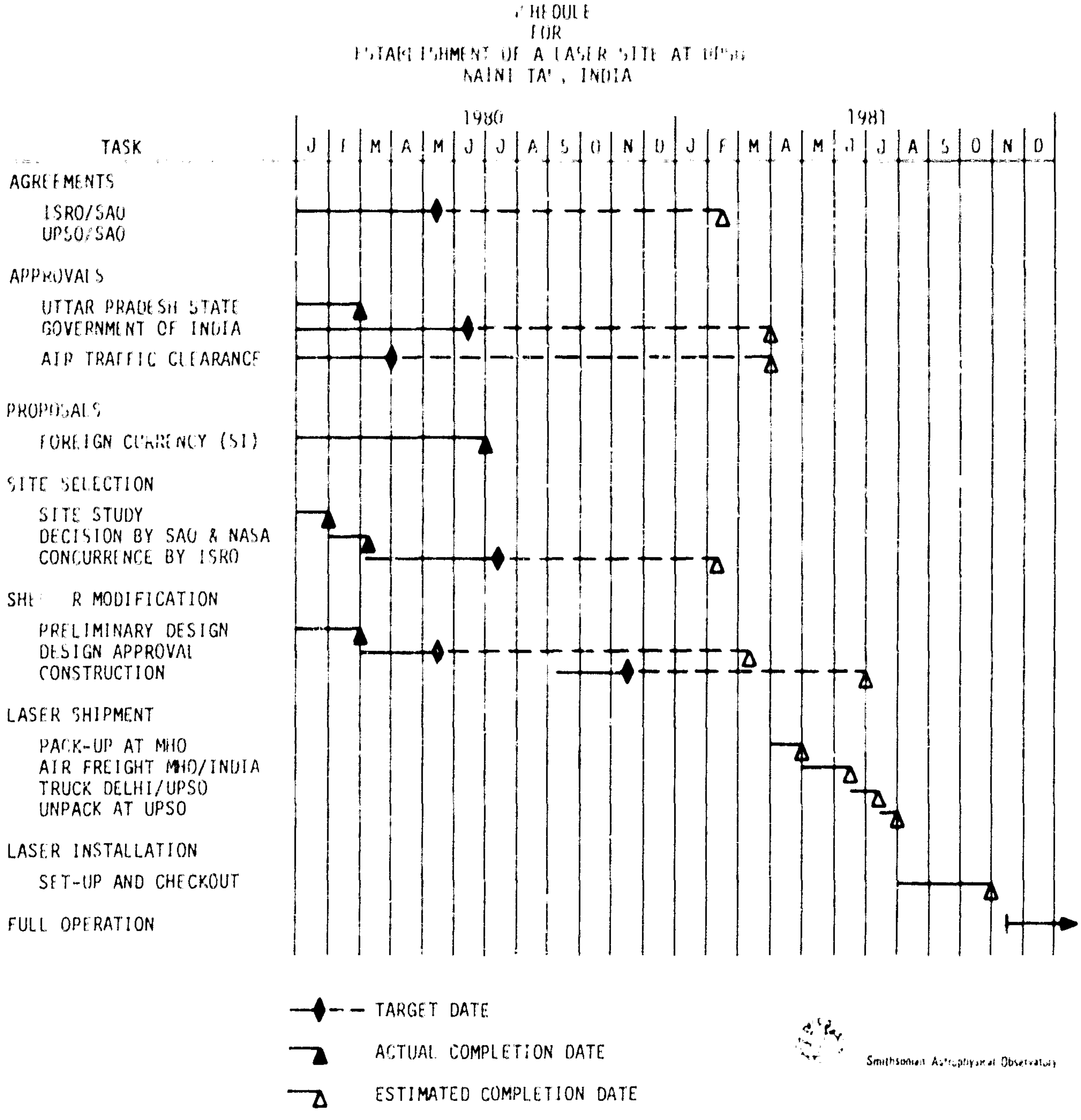
incurred within the United States.

4. The U.S. Embassy in New Delhi, would provide the necessary administrative and communications support to bring this project to fruition.

In the interim period, there has been some very limited communication with ISRO, mainly through the Embassy, which continues to convey a favorable position for ISRO. Discussions between NASA and ISRO, including discussion between Drs. Frosch and Dhawan, indicate that ISRO is still giving this program very serious consideration and a response will be forth coming in early 1981, after they have completed their long range planning.

Assuming an approval for the program in January, a revised schedule for the establishment of the laser station in Naini Tal is shown in Figure 7. The schedule is given in terms of calendar months. Based on these assumptions, our best estimate at this time is that the India station will be in operation by early FY 1982.

Figure 7.


SCHEDULE
FOR
ESTABLISHMENT OF A LASER SITE AT UPSO
NAINI TAL, INDIA
1980
1981
TASK
J F M A M J J A S O N D J F M A M J J A S O N D
AGREEMENTS
ISRO/SAO
UPSO/SAO
APPROVALS
UTTAR PRADESH STATE
GOVERNMENT OF INDIA
AIR TRAFFIC CLEARANCE
PROPOSALS
FOREIGN CURRENCY (SI)
SITE SELECTION
SITE STUDY
DECISION BY SAO & NASA
CONCURRENCE BY ISRO
SHELTER MODIFICATION
PRELIMINARY DESIGN
DESIGN APPROVAL
CONSTRUCTION
LASER SHIPMENT
PACK-UP AT MHO
AIR FREIGHT MHO/INDIA
TRUCK DELHI/UPSO
UNPACK AT UPSO
LASER INSTALLATION
SET-UP AND CHECKOUT
FULL OPERATION
TARGET DATE
ACTUAL COMPLETION DATE
ESTIMATED COMPLETION DATE
Smithsonian Astrophysical Observatory

10. LASER UPGRADING

Under revision 1 to the FY1981 Proposal (P987-6-80) and subsequent approval by NASA, SAO has embarked on a program of laser upgrading to bring the SAO lasers to 3-5cm accuracy and to improve data yield for the crustal dynamics program. The key elements of the program are to reduce the laser pulse width from 6 nsec to 2-3 nsec by modifying the pulse chopper and increasing the pulse repetition from 8ppm to 30ppm to increase the data yield. To accommodate the increased pulse repetition rate and to reduce range noise, we are replacing the waveform digitizer with an analog pulse processor and by using a better PMT and PMT base. System Signal to Noise, particularly during twilight and daylight ranging, is being increased with a redesign of the photoreceiver to accommodate a 3 Angstrom interference filter and a modification to the range gate generator to reduce the gate window by a factor of 10. Associated into these changes are modifications to hardware, software, and operational procedures.

The modifications are being implemented primarily for LAGEOS. All of the modifications will be applicable to some extent to the lower satellites; however, the higher angular tracking rates and the greater uncertainty in orbital position of the lower satellites will preclude some of the potential for higher data rates and narrow range gate windows.

The program will take approximately 18 months, and should have the lasers prepared for the next MERIT Campaign.

10.1 Increased Data Rate

The major limitations in pulse repetition rate for the SAO lasers has been the mount and the pulse processing in the Computer. In the case of LAGEOS, where the angular rates are very slow, the mount can operated at rates well in excess of 30 ppm and the computer becomes the limitation. The implementation of the analog pulse processor ameliorates this problem.

Increasing the laser pulse repetition rate from 8 ppm to 30 ppm requires modifications to (1) the laser power supply and (2) the laser control unit. All other hardware is presently compatible with the increased rate. The modifications to the power supply are being done by the SAO engineering staff with modules and components to be furnished by Laser Industries, Inc. Technical discussions are presently underway with Laser Industries. The current plan is to have them under contract in early CY 1981 for the required hardware. The modifications to the laser control units require that these units be replaced with new laser control units. These are now being designed and will be built under the direction of the Senior Electronics Engineer.

A prototype software package which runs at 30 ppm with simulated analog pulse processor data has been written and is operating at SAO. Efforts are underway to add operational features to the program. Changes in format and some control considerations will make it necessary to change some of the subsequent data processing software once the field program are completed.

10.2 Reduction in Laser Pulse Width

The laser pulse width will be reduced to 2-3 nsec by building a shorter ceramic Blumlein structure for the pulse chopper. Discussions are underway with Lasermetrics, Inc., the builders of SAO pulse choppers, who will fabricate the new Blumlein structure.

10.3 Improved Range Gate

The SAO lasers currently use a range window of 6-10 microseconds. This poses no difficulty during the nighttime hours; however, at twilight and under daylight conditions the system is very noisy, and operation on LAGEOS is precluded. To improve the system, SAO is modifying the range gate generator to oprated at windows down to 0.1 microseconds. Design of this modification to now underway. Some reformatting in the hardware and the addition of some circuit components.

In addition to the hardware modifications, the prediction software is also being modified to be compatible with submicrosecond predictions (see Section 5).

10.4 Modifications to the Photoreceiver

Improvements are also being made to the photoreceiver to improve range accuracy and the return signal to noise ratio. A new PMT (Amperex 2233) and a new PMT base have given considerable improvement in pulse shape and repreducibility. In addition, the

photoreceiver is being modified to accommodate a fast pulse shutter and a 3 Angstrom narrow band filter. This should provide an additional factor of 2.6 improvement in signal to noise from the present 8 Angstrom filter, and will offer protection for the PMT from daylight and laser backscattering.

The design of photoreceiver modifications has been completed. Vendors have been selected for the components to be ordered in January. The 3 Angstrom filter will be purchased from Daystar Filter Corp. The shutters, already tested at Mt. Hopkins, will be purchased from Vincent Associates.

10.5 Analog Pulse Detector

A fundamental element to the increased data rate and the improved accuracy is the analog pulse detector. Not only does this reduce considerable the data processing per pulse over the digitizer and thereby make the 30ppm mode possible, but for very narrow pulses it also avoids errors introduced through inadequate pulse amplitude sampling. In addition, it also avoids the inherent complexities of the WD2000 and the related pulse processing software.

SAO has built three different analog pulse processors which have been undergoing testing at Mt. Hopkins. All appear to give results at least recomparable to the WD2000; detailed tests are underway at Mt. Hopkins to demonstrate if one of the systems, or combination thereof is superior. The first processor uses a match filter (matched to the laser output pulse) with differentiator and a cross-over detector (discriminator with a low threshhold and a slope dependent arming circuit). The second

processor is a tapped delay line integrator with a cross-over detector. With this scheme, the taps from the delay line are summed and differenced to give effectively a pulse area differentiation which is then examined for the point of cross-over. The third detector is based on constant fraction discriminators.

Extended target calibrations are being used to assess the performance of each system, and to make a final decision on the system configuration for both the start and stop channels. We anticipate that the tests will be completed by late January and that a decision on final system configuration can be made in February after all of the data are evaluated. Many of the parts for the production systems have already been ordered.

11. PERSONNEL

11.1 Visitors

Several companies, who are potential Service Contractors in support of the SAO Mission Contract bid, were represented here at headquarters as SAO commenced meetings for the discussion of the Mission Contract proposal.

In August, Memphis Norman, a budget examiner from the Office of Management and Budgeting, came to Cambridge for general administrative discussions.

A number of field personnel visited Cambridge during this reporting period. Stephen Criswell an Donald Patterson visited during August while on home leave. Dana Seaman arrived in September for several days of technical discussions. William Dennison Rich, manager of the Brazil station, and David Hallenbeck, manager of the Peru station, took annual leave during November, and also visited SAO headquarters for discussions.

11.2 Personnel

In August, Mr. Dennis Anttila was hired as a new Observer for the Arequipa station; however he resigned shortly thereafter.

There were a few changes in headquarters personnel during this reporting period. In August, Eileen Brady joined our staff as a secretary. David Kirk Gilmore transferred from his position of Computer Technician in STADAD to the Optical and Infrared Astronomy Division at Mt. Hopkins, where he is a Physical

Science Technician. Jean Kintner joined our staff during November as a computer programmer, transfering from another part of the Observatory. Suzanne Romaine also transfered to another division, leaving the position of a computer programmer; Saeqa Dil replaced Suzanne during the latter part of December.

Walter Munn, Master Observer at Wallops Island, Virginia*, retired at the beginning of December.

11.3 Travel

Various headquarter personnel went to Perkin Elmer, an engineering firm in Wilton Connecticut, to deliver and pickup the photoreceiver mirrors undergoing modifications there.

Dr. Michael Pearlman attended various conferences and participated in administrative and technical discussions at NASA headquarters and Goddard Space Flight Center. Margaret Warner visited Wallops Island and the Smithsonian Institution during this reporting period.

Two of our engineers traveled to the Mt. Hopkins station during this six month period. James Maddox worked on upgrading of the photoreceiver and carried out tests with the PIN diodes during his stay in November. Noel Lanham arrived shortly thereafter for field trials with the prototype analog detector system and to perform maintenance on the Mt. Hopkins laser system in readiness for relocation to India.

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* Supported by NASA Contract NAS6-2910

APPENDIX A

SATELLITE TO SATELLITE DOPPLER TRACKING (SSDT)

FOR MAPPING OF THE EARTH'S GRAVITY FIELD

Semiannual Report No. 1

For the period 1 April 1980 through 30 September 1980

Grant No. NAG5-36

Principal Investigator
Dr. E. M. Gaposchkin

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center

December 1980

Smithsonian Institution
Astrophysical Observatory
Cambridge Massachusetts 02138

The Smithsonian Astrophysical Observatory
and the Harvard College Observatory
are members of the
Center of Astrophysics

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Co-investigators
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G. Colombo

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Semiannual Report No. 1

1. INTRODUCTION

This Semiannual Report covers the initial part of work done under NASA Grant NAG5-36, Study of the Feasibility of Satellite-to-Satellite Doppler Tracking for Mapping of the Earth's Gravity Field Suitable for Geophysics and Oceanography, and covers the period 1 April 1980 through 30 September 1980. The overall objectives of this grant are summarized in the next section. During this first reporting period, work was undertaken in support of three tasks. First, a general analytical study was undertaken to obtain simple relations about the sensitivity and resolution of the gravity field determination to three different types of observations. This study allows relatively inexpensive comparisons of different types of data and provides guidance for more detailed numerical modeling experiments. Second, careful conversion and upgrading of the computer software to generate simulated satellite to satellite tracking data. Third, initial development of the analytical solution for the satellite perturbations due to the anomalous geopotential. This analytical solution forms the basis of the Generalized Inversion Method to be used for mapping the geopotential at the earths surface from doppler measurements at satellite altitudes.

In addition during this period, SAO presented preliminary results at a GRAVSAT working group meeting at Goddard Space Flight Center on March 12-13, 1980.

2. OBJECTIVES

The Smithsonian Astrophysical Observatory (SAO) is supporting the NASA Geodynamics Program. One of the goals of this program is to use space techniques to study the fine structure of the earth's gravity field in length scales between 100 and 2000 km. The gravity field (or external potential) provides one of the few observations related to the earth's internal mass distribution and, therefore, the internal structure of the earth. Equally important is that the geoid (a surface defined by the external potential) the the reference to which changes in sea-surface elevation are referred. These sea-surface elevation changes can be measured with satellite-to-sea-surface altimeters such as Geos 3, Seasat, or Topex, and they contain information of the ocean circulation and eddy field. SAO will pursue the three topics summarized below:

1. We will investigate analytical solutions for the relative velocity of such configurations as high-low and low-low satellite systems. The relative velocity of two satellites is determined by the anomalous potential of the earth, among other things. Given a description of the anomalous potential, we can calculate the relative velocity to be measure with a SSDT system (the forward problem). These analytical expressions will be used to study the sensitivity of the SSDT system to the anomalous potential as a function of amplitude, wavelength, and system configuration.

2. Observations of relative velocity at satellite altitudes can be used to calcuate the anomalous potential at the earth's surface (the inverse problem). Three steps are required: 1) solution of the boundary value problem, 2) solution of the downward continuation problem, and 3) regularization at the earth's surface. Using analytical solutions for satellite motion, we propose to investigate two methods to solve these problems - generalized inverse methods and least squares collocations methods.

3. We propose to investigate a novel mission concept that uses two low satellites with moderate eccentricity. The two satellites would be in phase, in the same plane, but with their arguments of perigee differing by 180 degrees. Therefore, when one satellite is at perigee, the other will be at apogee, and the SSDT will measure the relative radial velocity (the high-low configuration). Approximately one-quarter revolution later, the SSDT will measure the relative along track velocity (the low-low configuration). Because of the secular motion of perigee, this system would sample the whole earth with measurements of both radial and along-track relative velocities. Such a mission configuation would also have a considerable advantage in terms of system lifetime and resolvability of the geopotential. We intend to carry out a system simulation of this mission concept, including a study of the recovery and separability of the geopotential.

3. ANALYSIS

The lack of simple closed analytic expressions relating the observable, dr/dt, with the anomalous potential, U, has hampered a careful discussion of a GRAVSAT mission. Consequently two schools of analysis have developed: a) those who plan and carry out large computer simulations (Douglas et.al. 1980, Schwarz, 1970, 1972), and b) those who extend very simplified models that are tractable (Breakwell, 1979, Fischell, 1978). Results from these simplified models can give useful insites and provide some guidance in planning extensive simulations. They are also useful in developing mission stratagies and profiles. Ultimately one expects these two approaches to agree, and then be able to select the particular technique appropriate for the problem at hand.

The analysis described here follows the ideas of Breakwell (1979). The extension to variable satellite spacing, satellite configuration, non - polar orbits, mixing of data types, and averaging methods are given, with some examples.

The satellite is assumed low, h/R << 1. , and the analysis is restricted to short wavelengths. In this case a flat earth approximation can be used and the estimation problem (downward continuation) is handled by two dimensional fourier transforms.

One can begin with the upward continuation of the surface potential using the flat earth form of Poisson's integral formula:

$$U(x,y,z2) = \frac{1}{2\pi}\int (z2 - z1)U(x,y,z1)*[x^2 + y^2 + (z^2 - z1)^2]^{-3/2}\, dA$$

where the height is in the z direction. If the two dimensional fourier transform of the potential is U(wx,wy,z) the fourier transform of (1) is found to be:

U(wx,wy,z2) = exp(-(z2-z1)w) * U(wx,wy,z1)

where w**2 = wx**2 + wy**2. The tranforms for various observables are easily found (following Breakwell), with U0=U(wx,wy,0) and h=z2 as:
Gradiometer
(Uxx,Uyy,Uzz,Uxy,Uxz,Uyz) =
U0*exp(-wh)*(-wx**2,-wy**2,-w**2,-wx*wy,-i*wx*w,-i*wy*w)
Velocity measurements
(Vx,Vy,Vz)=U0*exp(-w*h)*(1/V,wy/wx/v,-w/wx/V/i)
where i**2=-1. The possible measurements are combinations of these observables. The measurements considered are given in table 1. In these cases, the LO-LO is considered as two satellites at the same altitude (h) separated by a distance (Δ) traveling in the north south direction, i.e. parallel to the x axis. The HI-LO case is considered as two satellites, one above the other, at altitudes h1 and h2. For the preliminary analysis

considered here, the eccentric LO-LO is considered as contributing part of the data in the pure LO-LO configuration, and part in the pure HI-LO configuration. Note, that the non polar configurations are obtained by taking the appropriate combination of the x and y components.

TRANSFER FUNCTION FOR OBSERVATION $\zeta = H(\omega)\ U$

Observation	Transfer Function $H(\omega)$
Gradiometer	$\omega^2 e^{-\omega h}$
LO-LO	$e^{-\omega h} \frac{2\sqrt{-1}}{V} \sin \frac{\omega_x \Delta}{2}$
HI-LO	$(e^{-\omega h_1} - e^{-\omega h_2}) \frac{-\omega}{\sqrt{-1}\ V\ \omega_x}$

$V \cong 7 \times 10^5$ cm/sec

Table 1.

The potential $U(x,y,z)$ can be used to calculate surface data, gravity anomalies or geoid heights. The fourier transform of these surface data can also be calculated by straightforward formulae. However, the quantities of interest are averages of gravity or geoid. The traditional averaging algorithm is to average a square block of side a. These blocks are easy to calculate but difficult to deal with theoretically. An alternative is to chose a spherical cap of radius a. This gives relatively simple theoretical formulae, but one rarely actually deals with data averages in this way. A third way, was chosen by Breakwell for its "simplicity". It is a Gaussian smoothing function. In fact all these methods are easily treated, within the framework outlined above. We give in table 2, the transfer functions for these averaging methods.

Gravity Anomaly	Transfer Function	$n(\omega) = f(\omega)\, U$
Averaging Method		Geoid Height
Gaussian	$\omega\, e^{\frac{-\sigma^2 \omega^2}{2}}$	$\frac{e^{\frac{-\sigma^2 \omega^2}{2}}}{\gamma}$
Block Average of Side a	$\frac{\omega \sin a\omega x}{a\omega x} \frac{\sin a\omega y}{a\omega y}$	$\frac{1}{\gamma} \frac{\sin a\omega x}{a\omega x} \frac{\sin a\omega y}{a\omega y}$
Circular Average of radius a	$\omega \frac{J_1(a\omega)}{a\omega}$	$\frac{J_1(a\omega)}{\gamma a\omega}$

$$\omega^2 = \omega x^2 + \omega y^2$$

$$\gamma \cong 980 \text{ cm/sec}^2$$

Table 2. Transfer Functions for Averaging Algorithm

We are now in a position to estimate some scalar function from the random process U0 by:

$$\mathcal{J}(\omega) = f(\omega)U0(\omega,h) \qquad (2)$$

from a set of measurements by:

$$\mathcal{J}(\omega) = H(\omega)U0(\omega)+W \qquad (3)$$

where $H(\omega)$ is given in table 1, and $f(\omega)$ is given in table 2, and W is the fourier transform of the measurement errors. If $\mathcal{J}_{U0}$ is the spectral density of the surface potential variations, and Φ is a matrix of measurement error spectral densities, then an estimate of the spectral density of the estimated quantity (gravity anomalies or geoid heights) $\mathcal{J}_n$ is given by:

$$\mathcal{J}_n = \frac{\mathcal{J}_{U0}\ (\omega)f(-\omega)f(\omega)}{1+\mathcal{J}_{U0}\ H(\omega)\,\Phi^{-1}\,\mathcal{J}_{U0}} \qquad (4)$$

For this analysis we use Kaula's celebrated rule of thumb, U0(l)=GM/a*10**-5/l**2, for the spectral density of the surface potential.

Equations 1, 2,and 3 can be used to compare different data types, and distribution. Given the assumptions, these formulae are unlikely to give absolute accuracies. However, they should provide some assessment of the relative accuracy of some measurement systems, and some different spectral characteristics of these systems.

The first comparison is of the various averaging methods, and the sensitivity of the measurement systems. These results assume a polar satellite, a data rate of one per 10 seconds, and a mission life time of 90 days. Since all the statistical parameters scale with these figures, one can modulate the absolute magnitude of the result very easily. However, the relative size of the errors is insensitive to changing these parameters. The measurement accuracies are given for conservative and optimistic estimates for both gradiometers and relative velocity measurements. For purposes of establishing nomenclature recall that one Eotvos Unit is 10**-9 (cm/sec**2)/cm, and that one micron/sec is 10**-3 cm/sec. Table 3 gives the uncertainty of the gravity anomalies or geoid heights for a variety of averaging methods, and data types. Two points should be noted. First, the variety of averaging algorithms, give comparable results, and any one can be used for purposes of comparisons. Second, according to this simulation any of the proposed systems could achieve the mission objectives of a GRAVSAT.

COMPARISON OF AVERAGING CONVENTION AT DEGREE 180

System	σ	Geometry	Gaussian σ = 62.06 km		Square a = 110 km		Circle r = 62.06 km	
			Δg (mgal)	N (cm)	Δg (mgal)	N (cm)	Δg (mgal)	N (cm)
Gradiometer	2.5×15^3 EU	h = 200 km	0.18	1.11	0.08	0.91	0.18	0.75
Gradiometer	2.5×15^2 EU	h = 200 km	0.83	9.28	0.61	8.57	0.55	5.00
Eccentric	$1. \times 15^4$ cm/sec	200 × 600 km	0.22	0.80	0.07	0.33	0.22	0.73
LO-LO	$1. \times 15^3$ cm/sec		0.56	2.92	0.32	1.94	0.42	1.98
LO-LO	$1. \times 15^4$ cm/sec	h = 200 km	0.28	1.26	0.12	0.78	0.26	0.98
LO-LO	$1. \times 15^3$ cm/sec	Δ = 50 km	0.82	6.53	0.56	5.56	0,56	3.75
LO-LO	$1. \times 15^4$ cm/sec	Δ = 300 km	0.19	0.64	0.04	0.20	0.20	0.64

Table 3.

The gradiometer and satellite to satellite tracking measurments sample the geopotential spectrum in different ways. Figures 1, 2, and 3 display this sensitivity for a number of different data accuricies and orbital configurations. Figure 1 contrasts gradiometer accuracy, altitude, and sampling rate. The percentage of each harmonic of degree 1 that is recovered is plotted against degree. Clearly, increased accuracy, higher data rate, and lower altitude give greater accuracy. Modulating any of these mission parameters can improve (degrade) the accuracy. However, the shape of the curve is unchanged. Modulating these mission parameters only shifts the curve.

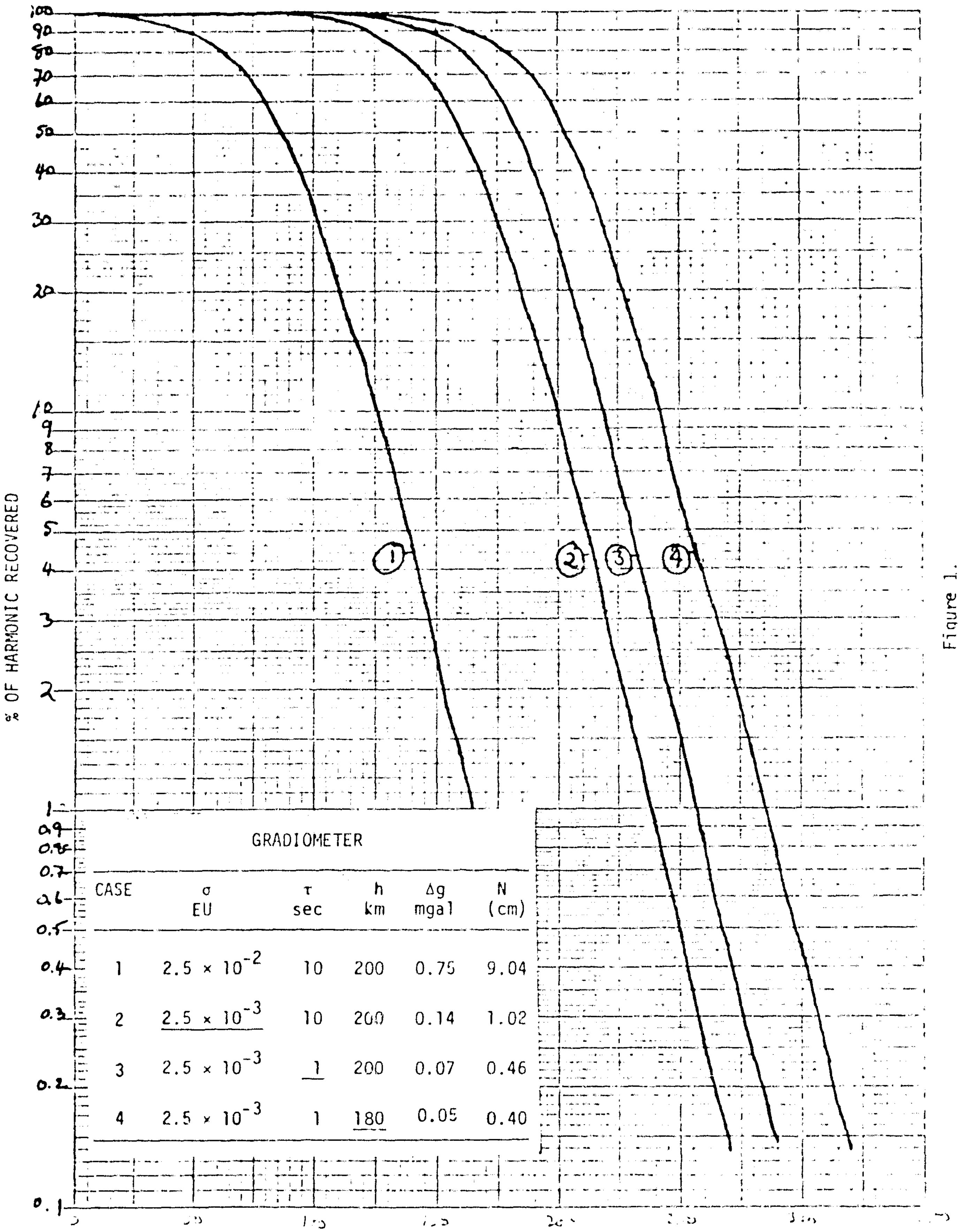
In figure 2, the LO-LO configuration is examined for different accuracy, altitude, and separation. Again, varying the mission parameters can improve (degrade) the result. However, varying separation distorts the pectral response. In curves 3 and 4, for 300 km spacing, the sensitivity is degraded. This is basically related to the well known fact that the two satellite system is insensitive to geopotential wavelengths comparable to the spacing of the satellites.

Figure 3 shows the spectral response of the eccentric LO-LO system. To some extent the reduced sensitivity to wavelengths comparable with the satellite spaceing is somewhat mitigated by having the verticle velocity measurement. However, there is still some distortion of the frequency response due to this commensurability.

The frequency response of the three measurement systems can be contrasted in ancther way. Figures 4,5,and 6 plot the error or uncertainty in each wavenumber (1) and a function of wavenumber, for the gradiometer, the LO-LO and the eccentric LO-LO. Here the frequency response is graphically displayed. Figure 5, shows of the uncertainty growing without limit for wavelengths corresponding to the satellite spacing. One would conclude that if the LO-LO system is adopted, then the spacing should be modulated to sample all wavenumbers equally. The gradiometer system has a somewhat more monotonic response. Especially for the higher degree gravity anomalies the gradiometer seems to have an advantage. The eccentric LO-LO shows some of the insensitivity at middle wavelengths as the baseline LO-LO system. However, the frequency response is broader, and finetuning the mission profile may result in a uniform spectrum.

In figure 7 an overall comparison of the system response of all three measurement systems is given. With the adopted mission parameters, the gradiometer seems to have the best performance. However, all of these curves are relative. This figure is more useful to estimate the tradeoffs for spectral response, than for absolute accuracy estimates. For example, it is clear that when the gradiometer sensitivity begins to decrease, it fall more sharply than, say, the eccentric LO-LO system.

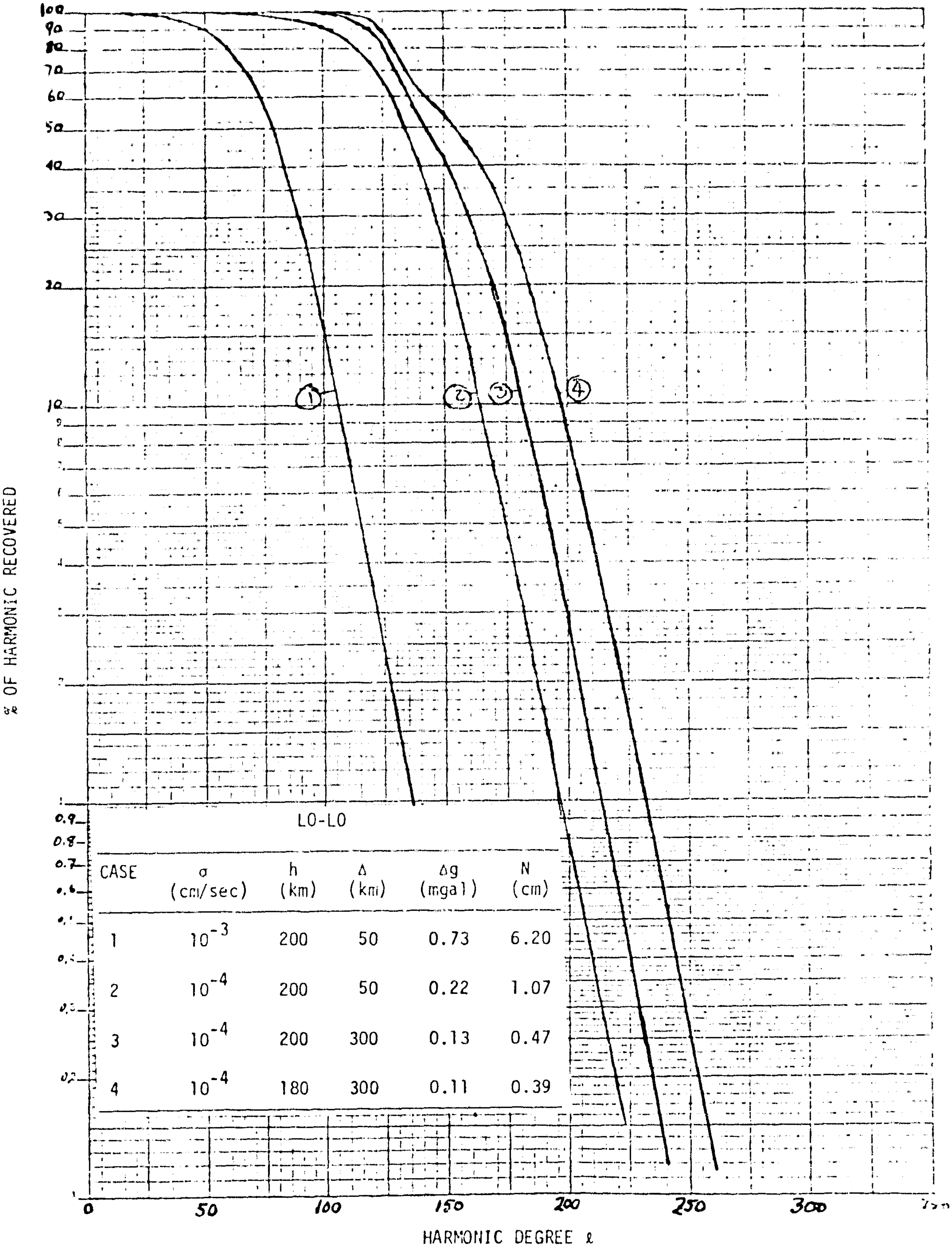
GRADIOMETER



GRADIOMETER

CASE	σ EU	τ sec	h km	Δg mgal	N (cm)
1	2.5×10^{-2}	10	200	0.75	9.04
2	2.5×10^{-3}	10	200	0.14	1.02
3	2.5×10^{-3}	1	200	0.07	0.46
4	2.5×10^{-3}	1	180	0.05	0.40

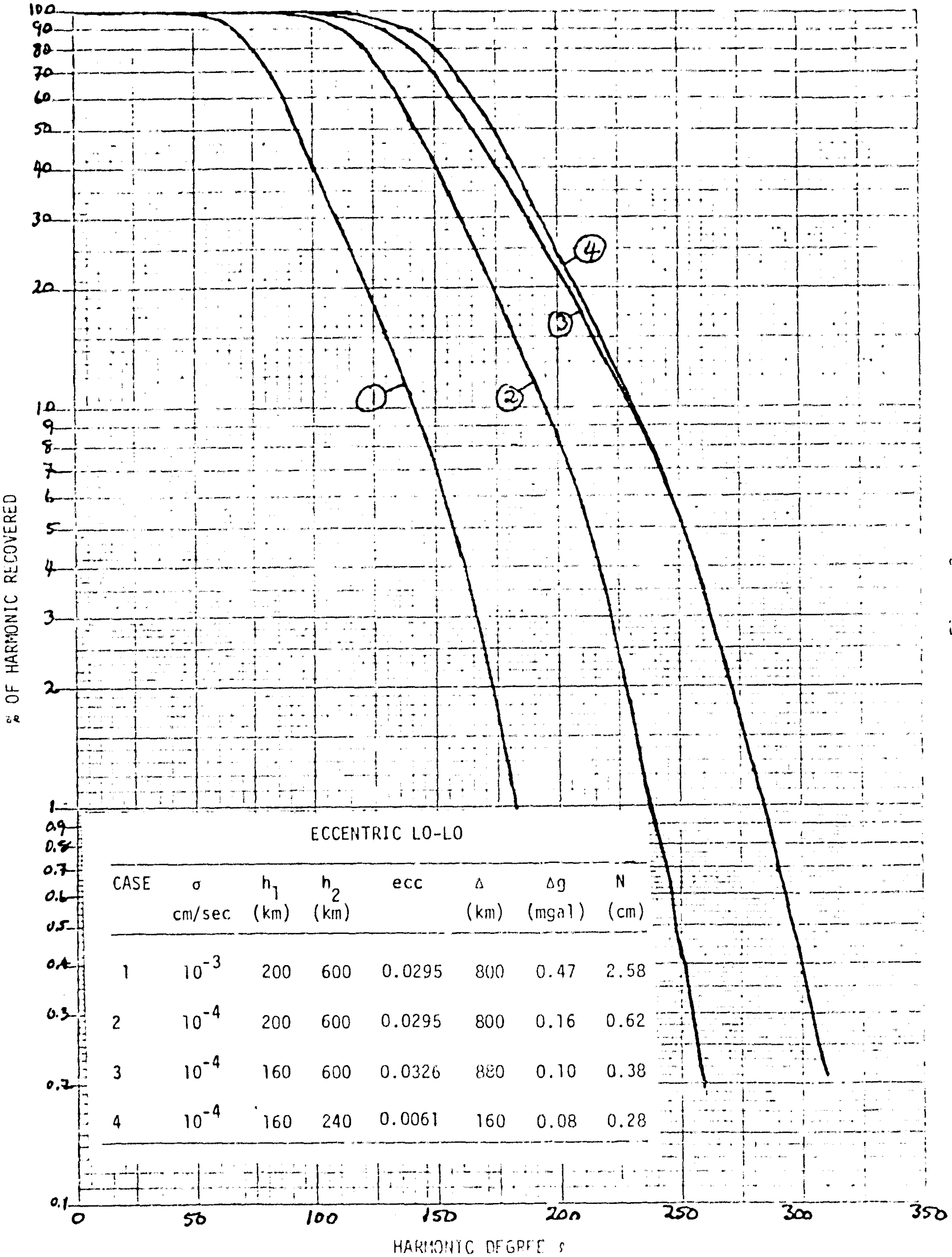
Figure 1.



LO-LO

CASE	σ (cm/sec)	h (km)	Δ (km)	Δg (mgal)	N (cm)
1	10^{-3}	200	50	0.73	6.20
2	10^{-4}	200	50	0.22	1.07
3	10^{-4}	200	300	0.13	0.47
4	10^{-4}	180	300	0.11	0.39

Figure 2.



ECCENTRIC LO-LO

CASE	σ cm/sec	h_1 (km)	h_2 (km)	ecc	Δ (km)	Δg (mgal)	N (cm)
1	10^{-3}	200	600	0.0295	800	0.47	2.58
2	10^{-4}	200	600	0.0295	800	0.16	0.62
3	10^{-4}	160	600	0.0326	880	0.10	0.38
4	10^{-4}	160	240	0.0061	160	0.08	0.28

Figure 3.

Figure 4.

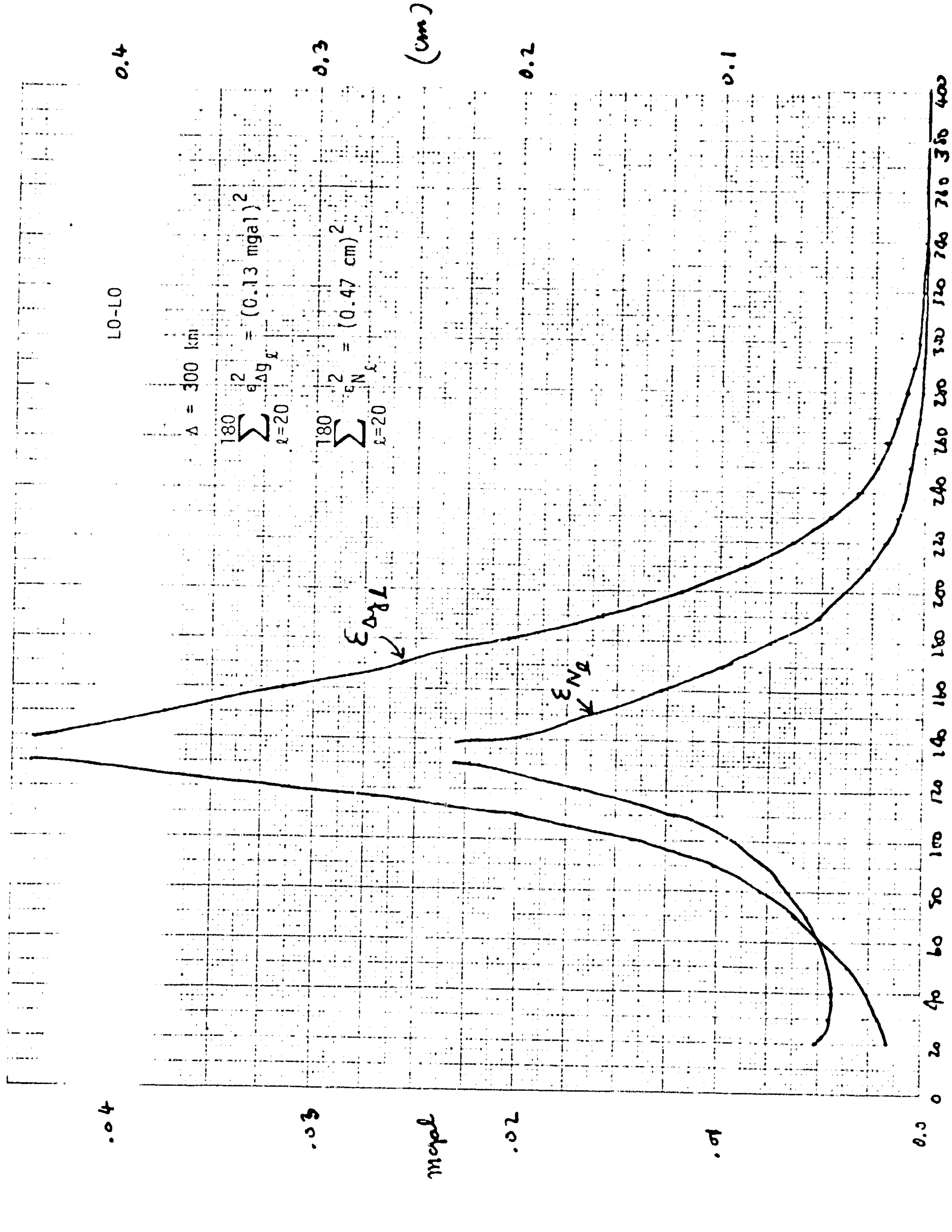

LO-LO
Δ = 300 km
$\sum_{\ell=20}^{180} \epsilon^2_{\Delta g_\ell} = (0.13 \text{ mgal})^2$
$\sum_{\ell=20}^{180} \epsilon^2_{N_\ell} = (0.47 \text{ cm})^2$
$\epsilon_{\Delta g_\ell}$
ϵ_{N_ℓ}
mgal
.04
.03
.02
.01
0.0
(cm)
0.4
0.3
0.2
0.1
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
ℓ

Figure 5.

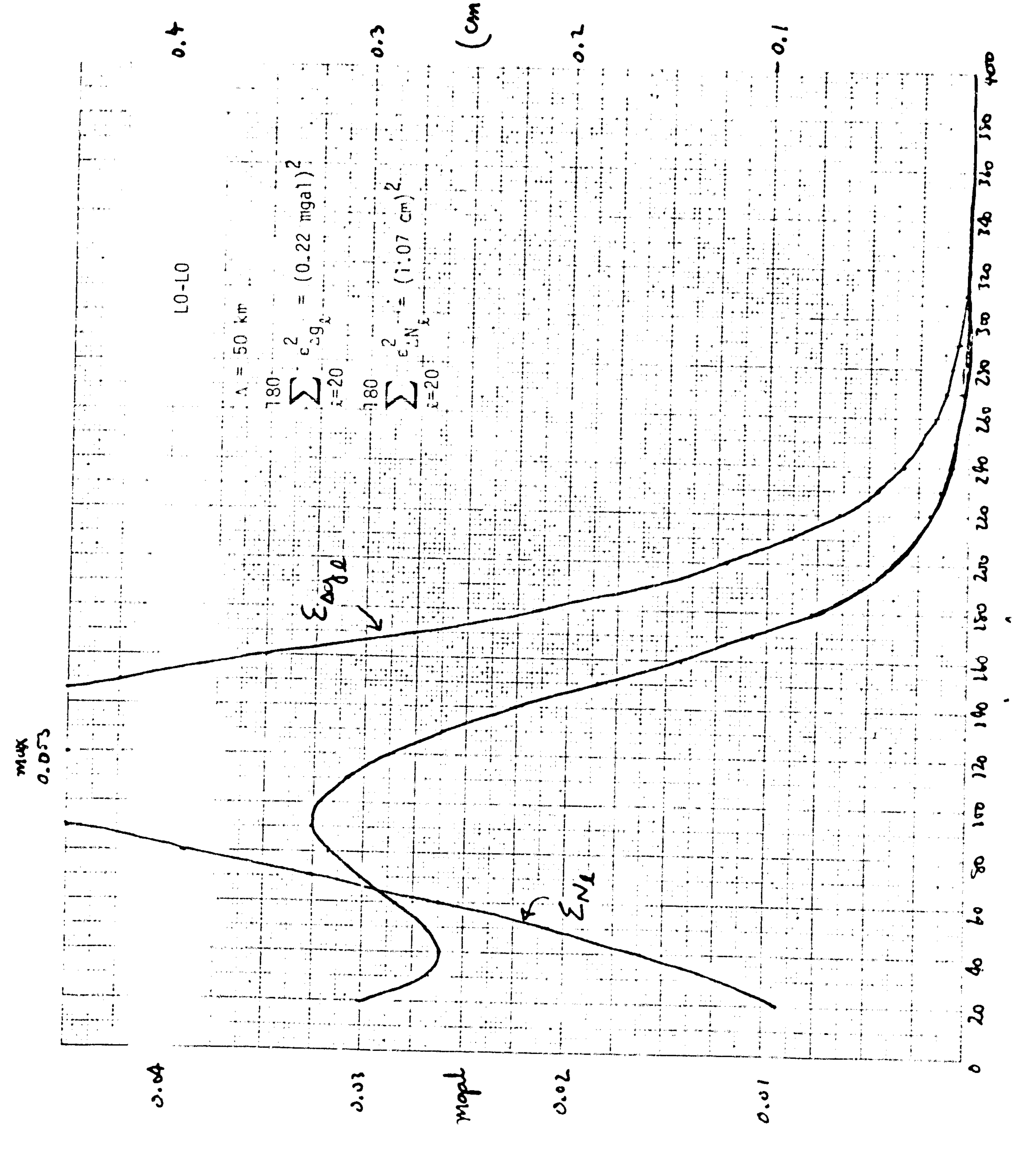

LO-LO
A = 50 km
$\sum_{l=20}^{180} \epsilon^2_{\Delta g_l} = (0.22 \text{ mgal})^2$
$\sum_{l=20}^{180} \epsilon^2_{N_l} = (1.07 \text{ cm})^2$
max 0.053
(cm)
mgal
0.4
0.3
0.2
0.1
0.04
0.03
0.02
0.01

Figure 6.

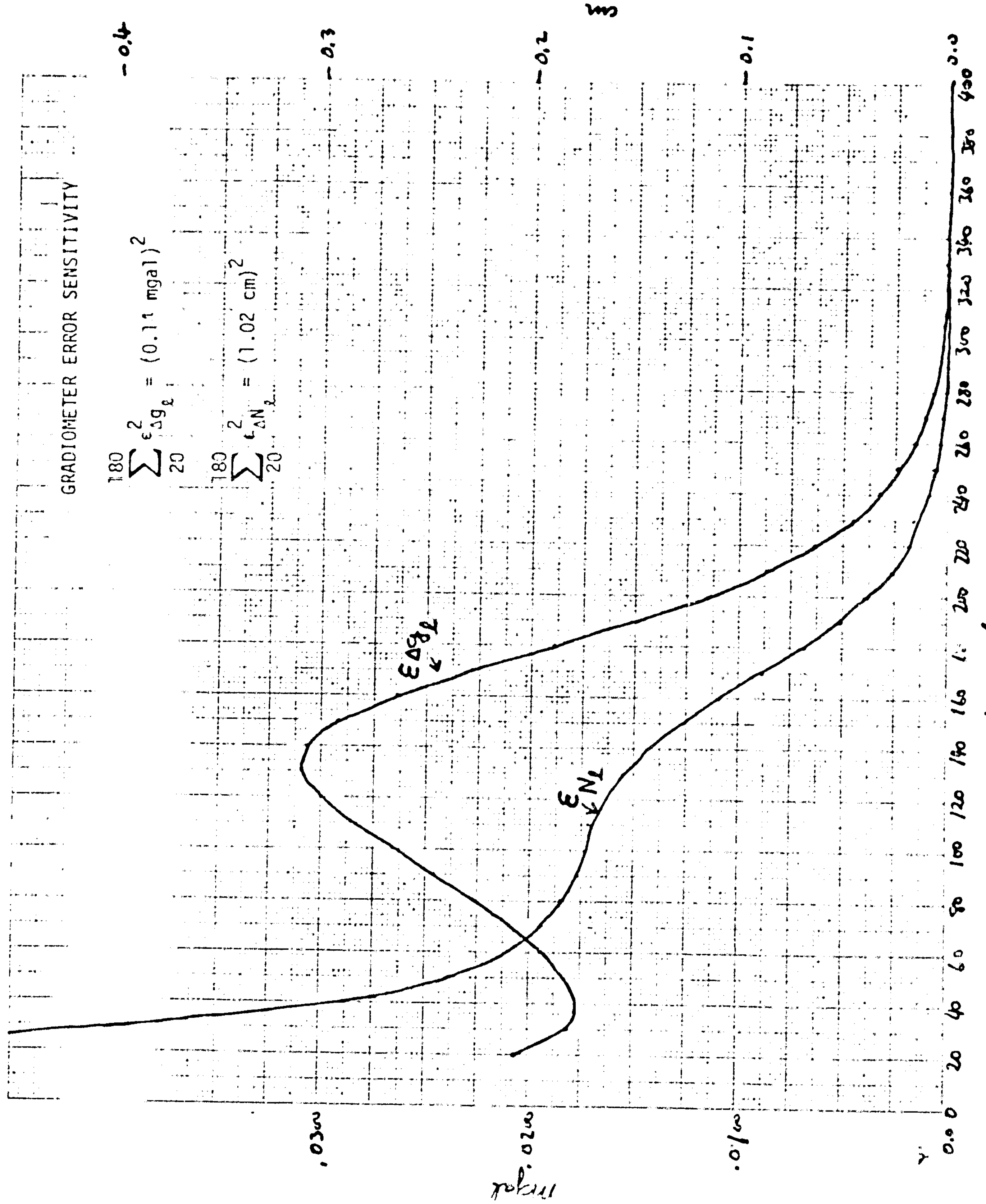

GRADIOMETER ERROR SENSITIVITY
$\sum_{20}^{180} \epsilon^2_{\Delta g_\ell} = (0.11 \text{ mgal})^2$
$\sum_{20}^{180} \epsilon^2_{\Delta N_\ell} = (1.02 \text{ cm})^2$
$\epsilon_{\Delta g_\ell}$
ϵ_{N_ℓ}
cm
0.0
0.1
0.2
0.3
0.4
mgal
.0300
.0200
.0100
0.0
ℓ
0
20
40
60
80
100
120
140
160
200
220
240
260
280
300
320
340
360
380
400

Figure 7.

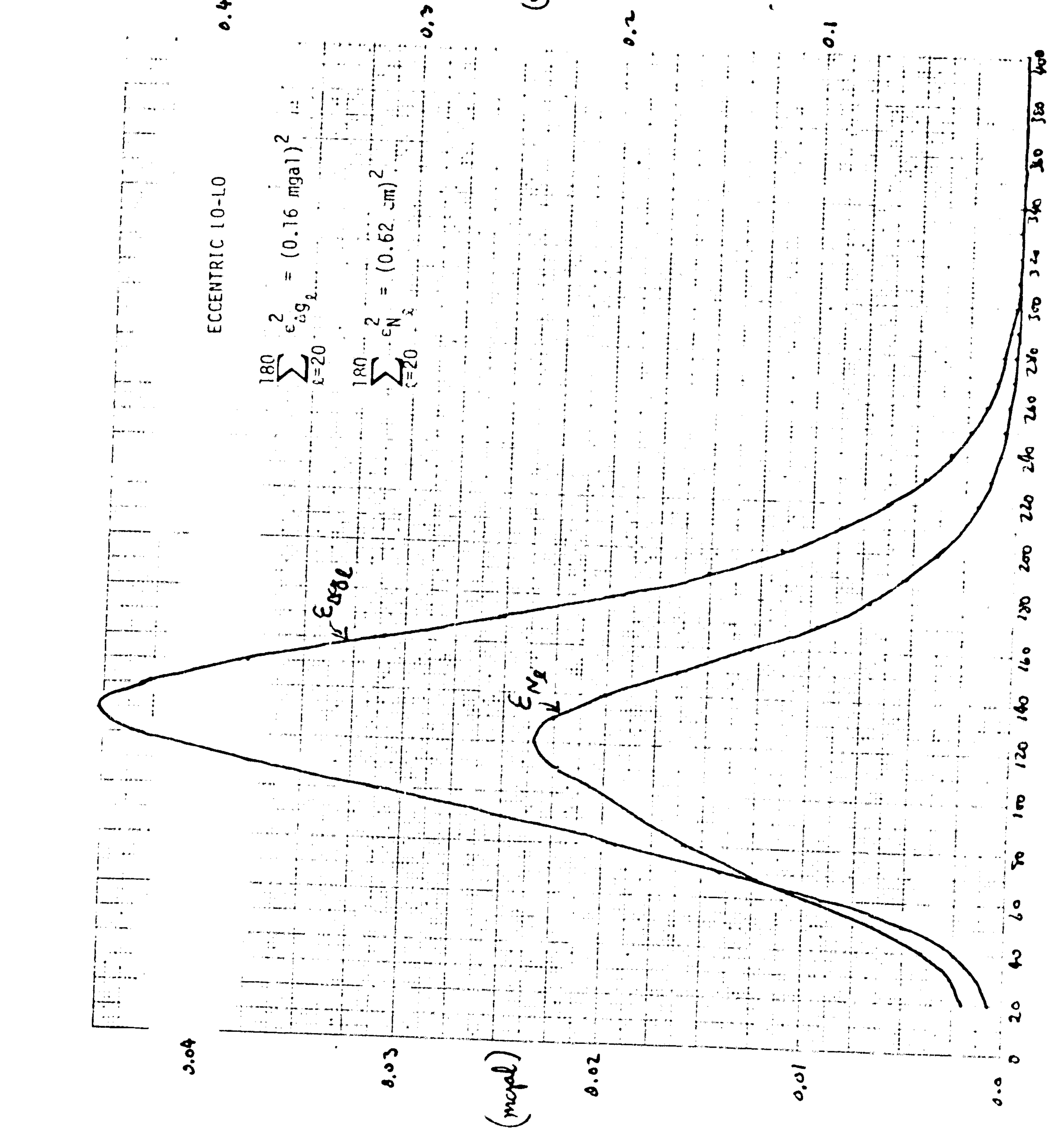
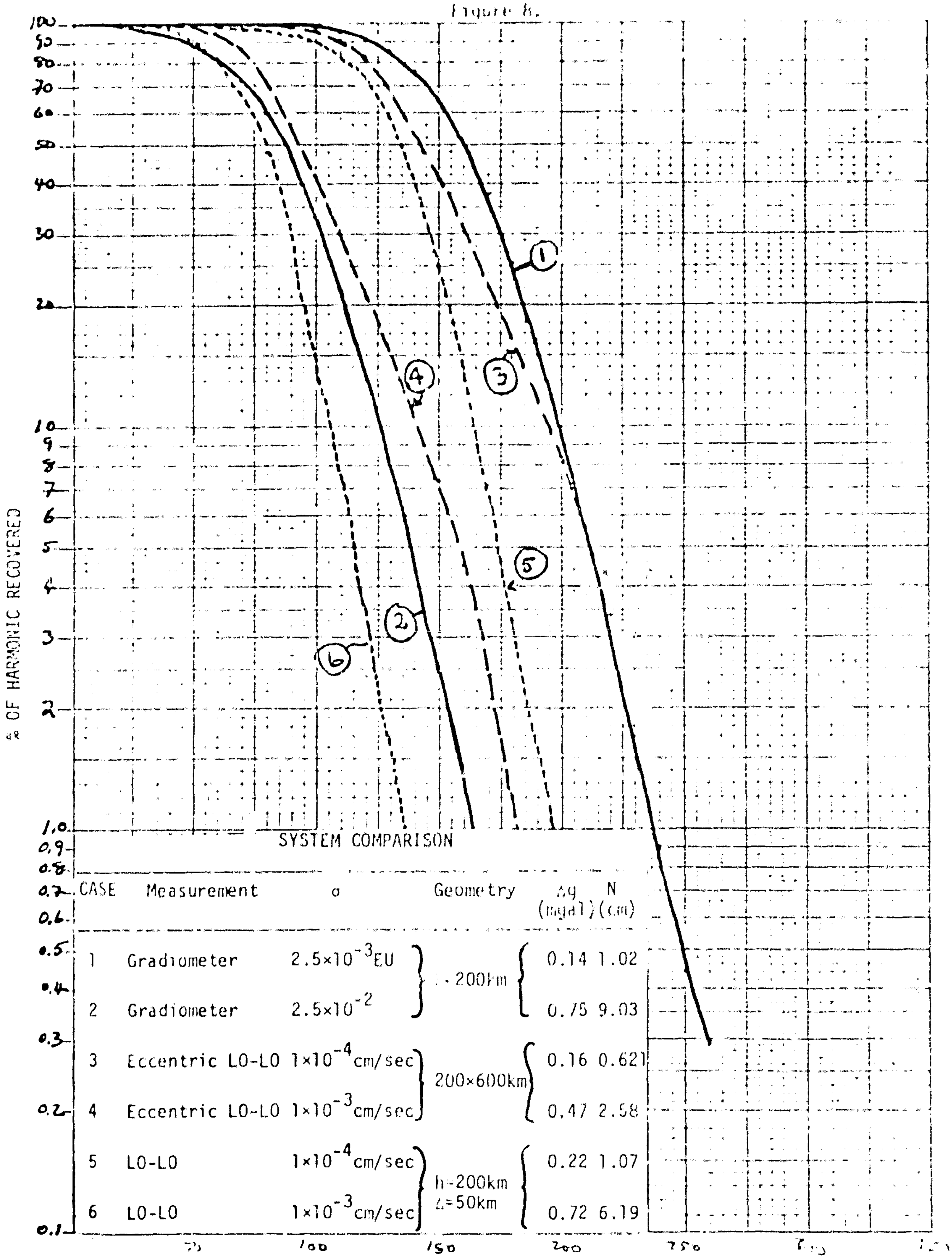

ECCENTRIC 10-LO
$\sum_{\ell=20}^{180} \epsilon^2_{\Delta g_\ell} = (0.16 \text{ mgal})^2$
$\sum_{\ell=20}^{180} \epsilon^2_{N_\ell} = (0.62 \text{ cm})^2$
$\epsilon_{\Delta g_\ell}$
ϵ_{N_ℓ}
(mgal)
0.0
0.01
0.02
0.03
0.04
(cm)
0.1
0.2
0.3
0.4
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400

Figure 8.



SYSTEM COMPARISON

CASE	Measurement	σ	Geometry	Δg (mgal)	N (cm)
1	Gradiometer	2.5×10^{-3} EU	h=200km	0.14	1.02
2	Gradiometer	2.5×10^{-2}		0.75	9.03
3	Eccentric LO-LO	1×10^{-4} cm/sec	200×600km	0.16	0.621
4	Eccentric LO-LO	1×10^{-3} cm/sec		0.47	2.58
5	LO-LO	1×10^{-4} cm/sec	h=200km Δ=50km	0.22	1.07
6	LO-LO	1×10^{-3} cm/sec		0.72	6.19

4. SOFTWARE DEVELOPMENT

Software development for the analysis can be divided into two categories. The first consists of the modification and testing of already existing routines. Under this heading fall the various routines that make up a numerical integration software package for calculation of satellite trajectories. Briefly, this program takes as input the initial Kepler elements or state vectors of one or more satellites and integrates the equations of motion to obtain the positions and velocities of the satellites at any later time. Output includes the relative line-of-sight velocity between the satellites in the relevant case of two satellites. The force acting on each satellite includes the force of the earth's gravitational field (central and non-central parts) and various other effects that may be switched on or off as desired. These additional effects include radiation pressure, atmospheric drag, and the gravitational attraction of the sun and moon. An additional feature is the option of including surface layer density gravity anomalies of the earth's gravitational field of any dimension and intensity at any position on the earth's surface. This feature is of course particularly relevant to the present analysis since the detection of such gravitational anomalies is the object of the low-low Doppler experiment. The integrator program can be used to generate reference data, against which we can compare the results of the analytically determined values of the relative velocities, thus obtaining a measure of the accuracy of our analytical formulae. The integrator could also be used in conjunction with the inverse problem analysis.

The integrator had originally been written for a CDC 6400 computer. Most of the routines had been converted for use on the SAO VAX 11/780 computer, but some had not. The first requirement was to make sure all the routines were converted and that the program was working correctly. This has been accomplished. The critical quantity for our analysis is the relative line-of-sight velocity between the two satellites. To test whether the integrator was performing its job with sufficient accuracy, we used the accuracy of the relative velocity as the criterion. We compared relative velocity output from the integrator program with the analytical values obtained by solving the Kepler equation for corresponding times, given the same initial conditions, for the case of simple two-body motion. The accuracy was well within the limits required. Typically, the difference in relative velocity obtained by the two methods was 0.03-0.04 micrometer/sec, corresponding to a relative error of 10^{-8} to 10^{-7}.

The next stage in testing the integrator routine was to determine the sensitivity of the integrator to graininess of the surface layer gravitational anomaly. For example, the effect of a single 110km x 110km surface anomaly on the the satellite orbit is not the same as that of the same surface area with the same intensity divided into 9 equal surface patches, and so on. What we needed to determine was the limit at which further division of the surface area into a smaller grid no longer caused a change in the relative line-of-sight velocity (the experimentally determined quantity in a Doppler experiment) greater than the hoped-for accuracy of the experiment. This meant the point at which the change brought about by a finer grid was less than a micrometer/sec.

The results of this study were that with both satellites at 200 km altitude a 100 mgal anomaly on a 110km x 110km surface patch required an 11x11 grid (121 subpatches) to obtain the desired accuracy in relative velocity, and at 150 km altitude a 13x13 grid was required. Since the computer time required rises with the number of surface patches, this result emphasizes the desirability of obtaining analytical formulas for the relative velocity components, which is one of the primary goals of the study.

The second category of software development is that of new computer programs to be used in the determination of relative velocity components as a function of time (and position) for an arbitrary surface anomaly distribution and for the inverse problem of determining the surface anomaly distribution from the relative velocity. At present, we are in the process of developing a program to determine the relative velocity components for the case of area mean anomalies using formulas we have derived. The first tests will be made with the simple two-body central force as the background force, with the important J2 harmonic term added later. configurations.

5. PLANS

The program we plan to follow in order to achieve the objectives outlined above may be briefly summarized:

1) Continue to develop software for obtaining perturbed relative velocity components with minimum expenditure of computer time in order to make computer simulations practical for general surface layer density gravity anomaly distributions as outlined above.

2) Concurrently to develop and test inversion methods for obtaining gravity anomaly distributions from simulated velocity data, studying the sensitivity of the results to variations of relevant parameters such as satellite height, orbital parameters, and the intensity and distribution of density gravity anomalies.

3) To procede by studying the simplest cases first, i.e., simple two-body motion plus mean surface layer anomalies, and then adding more perturbative terms to obtain progressively more realistic models as each level of approximation is understood for the different orbital configurations.

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APPENDIX B

INVESTIGATE THE TIME EVOLUTION OF THE CORRELATION BETWEEN BATHYMETRY AND THE GEOID HEIGHT IN THE PACIFIC OCEAN

Contract NA79SAC00739

Quarterly Reports Nos. 4 & 5

For the period 1 May through 31 October 1980

Principal Investigator

Dr. Micheline C. Roufosse

Prepared for

National Oceanic and Atmospheric Administration
Rockville, Maryland 20852

December 1980

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

INVESTIGATE THE TIME EVOLUTION OF THE CORRELATION BETWEEN BATHYMETRY AND THE GEOID HEIGHT IN THE PACIFIC OCEAN

Quarterly Report Nos. 4 & 5

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For the period 1 May through 31 October 1980

Dr. Micheline C. Roufosse, Principal Investigator

December, 1980

During the reporting period ending on July 31, 1980, no work was performed on this project. Results of the work prior to this period were presented at the spring AGU meeting in Toronto, Canada, May 25-27. No project funds were spent during that period except in support of this presentation.

During the last reporting period, from 1 August through 31 October, most of the work that was done dealt with the northern section of the Mid-Atlantic Ridge and the Azores area, where we want to study the short and intermediate wavelengths in the geoid height spectrum. In order to accomplish this, we retrieved all the SEASAT and GEOS 3 satellite passes which crossed the area between latitudes 0 degrees and 40 degrees North and between longitudes 300 degrees and 360 degrees East. We retrieved 29 SEASAT passes in that region but, unfortunately, many passes were almost repetitive; these 29 passes offered only 3 distinct groups of passes. Therefore, we decided to complement this data

set with GEOS 3 data. The GEOS 3 data that were used have been corrected for bias and trend. The long wavelengths (>4000 km) in the geoid heights have been removed by subtracting a reference geoid calculated with the GEM-7 coefficients up to degree and order 10. The geoid heights are in the process of being contoured using Mercator projections in collaboration with Drs. Parsons (Massachusetts Institute of Technology) and McKenzie (U. Cambridge, England). By suppressing broad features of large magnitude, the process of filtering out the long wavelength features increases the resolution of the geoid obtained. These remaining geoid heights will then be studied in terms of the aging and cooling of the lithosphere.

The small wavelength features in the geoid are studied on a track by track basis. The correlation between the geoid heights and the bathymetry is studied by using a thin elastic plate model with variations in crustal thickness. Typical crustal thicknesses along the North Atlantic Ridge which are derived by this method are of the order of 10 km, in agreement with observations in that region.

Predictions are obtained in the Azores area using an Airy model and a thin elastic plate model. The results obtained so far tend to favor the Airy model with a crustal thickness of about 20 km. Further work is necessary, however, in order to gain more confidence in the validity of these preliminary results.

Estimated Funding Status

Of the total amount of \$50,000, approximately \$29,600 have been expended. This represents about 60% of the fund; about 60% of the total work has been completed.

APPENDIX C

RESEARCH OF THE STATE OF CONVECTION

IN THE EARTH'S MANTLE

Grant NCC 5-10

Semi-Annual Progress Report No. 3

For the period 1 May 1980 through 30 October 1980

Principal Investigator

Dr. Micheline C. Roufosse

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

December 1980

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

1. Introduction

In this work, we will study the behavior and mechanical properties of the lithosphere. This is a prerequisite to an understanding of the mechanisms and processes that occur in the earth's mantle, which are masked by the lithosphere. For this study, we will use the geoid heights derived from the GEOS 3 and SEASAT radar altimeters. The study of the correlation existing between bathymetry and geoid heights gives information on the mechanical properties of the lithosphere such as its thickness, which is related to the age of the lithospheric plate. By probing several locations spanning varied temporal situations, we are able to retrace the time evolution of the lithospheric plates.

We also believe that a systematic study of this type will lead to one of the following predictive capabilities: location of unknown seamounts from the knowledge of the geoid heights, prediction of gravity field from the knowledge of the topography and past history of the relief, or insight into the history of a region from the knowledge of both topography and geoid heights. To achieve this aim, several seamount chains, islands, and ridges must be investigated. Several geographical areas have already been studied, including the Walvis Ridge in the Southern Atlantic Ocean and several seamount chains in the Central Pacific Ocean.

2. Method

In this paper, we have restricted ourselves to the study of linear bathymetric features, i.e., seamount chains. In studying such features, it is legitimate to consider individual satellite passes crossing the chain of seamounts at an angle as close as possible to 90 degrees. It is therefore unnecessary to go through the tedious procedure of adjusting all satellite passes into a coherent network by calculating and removing a bias and trend. Furthermore, dealing with individual satellite passes is ideal for studying the evolution along a seamount chain.

To account for the geoid signals observed so far, two models were developed: the thin-elastic-plate model and the Airy model (see, for example, McKenzie and Bowin, 1976). The thin-elastic-plate model applies when a load has been developed on a thin plate of finite thickness which is subsequently deformed. The magnitude and wavelength of the deformed area depend mostly on the flexural rigidity, which is itself proportional to the cube of the lithospheric thickness. The Airy-type model applies when the load was created simultaneously with the lithosphere (or on zero thickness lithosphere) and developed light roots in order to establish local or regional isostatic equilibrium. The methodology has been described in Roufosse (1979) and will be summarized here.

The first step in our procedure is to calculate theoretical filters in wavenumber space using variable parameters for both models (for example, see Figure 1). We then Fourier-transformed these functions in normal space. Next, the bathymetry was reconstructed as rigorously as possible along the subsatellite position using available contour charts (the Uchupi charts were used in the Atlantic Ocean). Lastly, the filters were convolved with the bathymetry in order to produce a set of theoretical geoid profiles to be compared with the observed geoid heights.

3. Work Performed During This Reporting Period

Much of the work consisted of organizing and editing the SEASAT radar altimeter data. The data are organized into individual files, each corresponding to a specific revolution number and further divided into sections corresponding to specific oceans. A program has been written to retrieve the satellite passes crossing a given geographical area.

Hawaii, in the Pacific Ocean, was chosen as the test area. An extensive study of this area, using the GEOS 3 radar altimeter data, has been done at SAO in collaboration with Dr.B.Parsons (Roufosse, M.C., Parsons, B.E., EOS Trans., A.G.U., 58, 1213, 1977). Ninety SEASAT passes have been retrieved, plotted, and edited in this region in order to assess, in a known case, the

gains in accuracy offered by SEASAT, and therefore indicate which steps should be taken next. GEOS 3 has been proven to be inadequate for studying features that offer a weak geoid signal, such as the East Pacific Rise, because the noise level was too high. Figure 1 shows a comparison between the geoid heights derived from GEOS 3 and SEASAT over the Hawaiian Seamount chain after the SEASAT data has been edited. The obvious gain in accuracy obtained and the low noise level observed with SEASAT will make it possible to study such interesting features as the East Pacific Rise as soon as the Southern Hemisphere data have been received.

The SEASAT data received did not prove to be fully adequate for the work proposed; therefore, we used a combination of SEASAT and GEOS 3 data.

The two areas that look most promising in the SEASAT data set available at this time are the New England seamounts and the northern section of the Mid-Atlantic ridge.

Two typical passes over the New England seamounts can be seen on the top profiles of Figures 2 and 3. The signals observed have a wavelength of 150 to 200 km and an intensity of 2 to 4 m. It is similar to the signal observed in the Marshall-Gil[illegible]t seamounts area.

The correlation study between the bathymetry and the geoid height yields information on the mechanical properties of the lithosphere; in this case, all the values found for the flexural rigidity are very low. These values range between 1 x 10^{29} and 4 x 10^{29} dyne-cm. The lithosphere is known to be very old in this region and therefore it is very strong. In order to account for the low values of the flexural rigidity, we had to postulate that the seamounts were very old and, therefore, were formed where the lithosphere was younger and thinner. The information gathered on the age of the seamounts confirms that hypothesis.

We also studied the Rio Grande Rise in the South Atlantic Ocean. This area was chosen in order to be compared with the previously studied Walvis Ridge area and because it is located symmetrically with respect to the Mid-Atlantic Ridge. The geoid signals present in the Rio Grande Rise region are weak and broad and mainly resemble those observed in the eastern and central sections of the Walvis Ridge. At this point in the study, we believe that the Rio Grande Rise has been formed simultaneously with the eastern and central sections of the Walvis Ridge by a hot spot located on the Mid-Atlantic Ridge. An Airy-type model of compensation best describes the signal observed. Because the SEASAT data in the Southern Hemisphere was not available until very recently, the study had to be completed with GEOS 3 data for good data coverage.

Now, we are in the process of retrieving several passes over the northern Mid-Atlantic Ridge and over the Azores Islands in order to study both the short and intermediate wavelengths that are present in the geoid spectrum.

Twenty-nine SEASAT passes and sixty GEOS 3 passes have been retrieved in that area. The GEOS 3 data are being filtered for long wavelengths (a reference geoid of degree and order 10 calculated with GEM 7 is removed from the raw data), and corrected for bias and trend using Dr. Rapp's information. It will then be plotted on Mercator projection in a collaborative effort with Dr.Parsons (MIT) and Dr.McKenzie (Cambridge University, U.K.). This map will give information on the intermediate wavelengths contained in the geoid and will be suitable for a time dependence study. The SEASAT data are studied on a track-by-track basis, and attention is focussed on the small wavelength features. We are presently in the process of retrieving the bathymetry along individual passes using all available information.

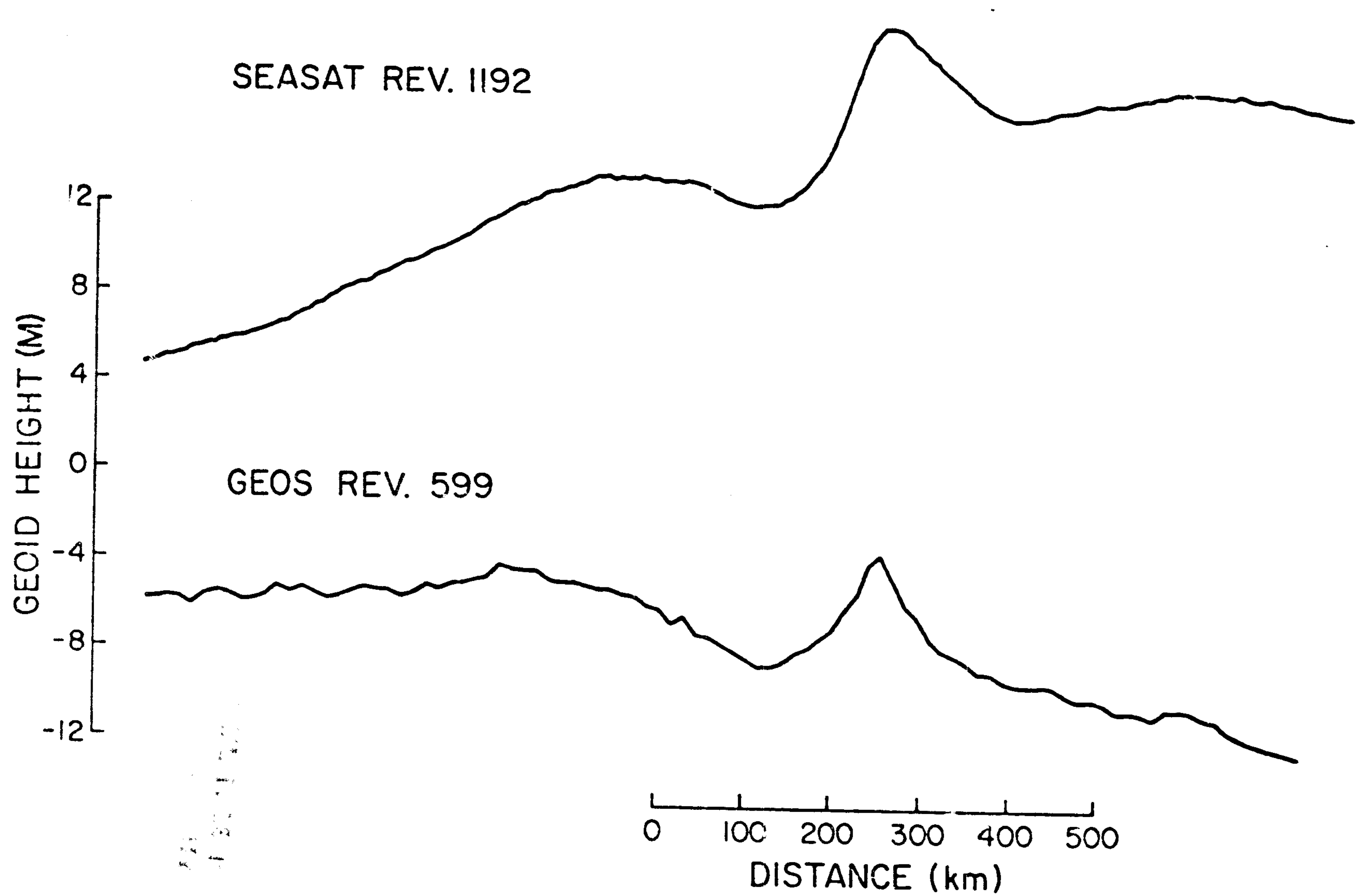

Figure 1. Comparison of geoid height over the Hawaiian Seamount chain (Geos 3 and Seasat Data).

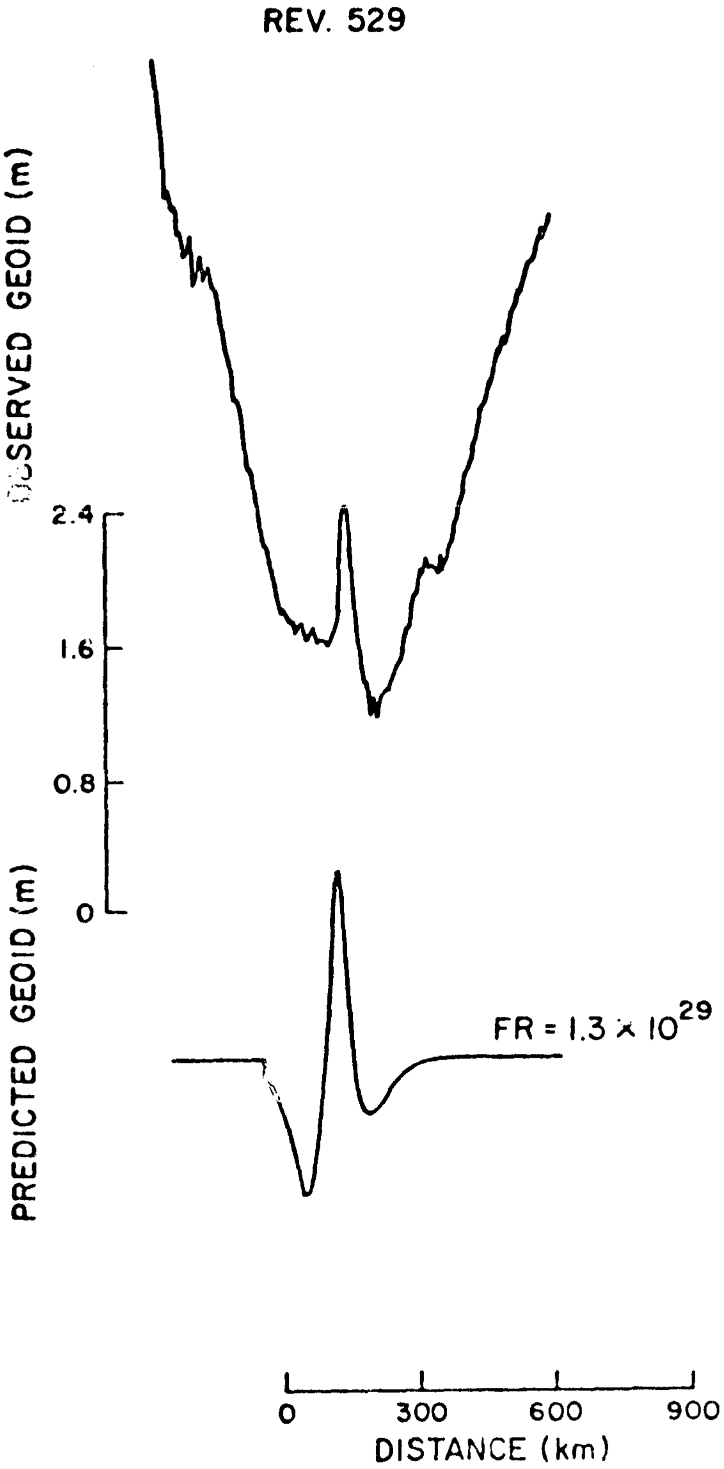

Figure 2. The top profile represents the observed geoid heights for the Seasat revolution number 529 over the New England seamounts. The bottom profile represents the predicted geoid heights calculated with a value for the flexural rigidity of 1.3×10^{29} dyne-cm.

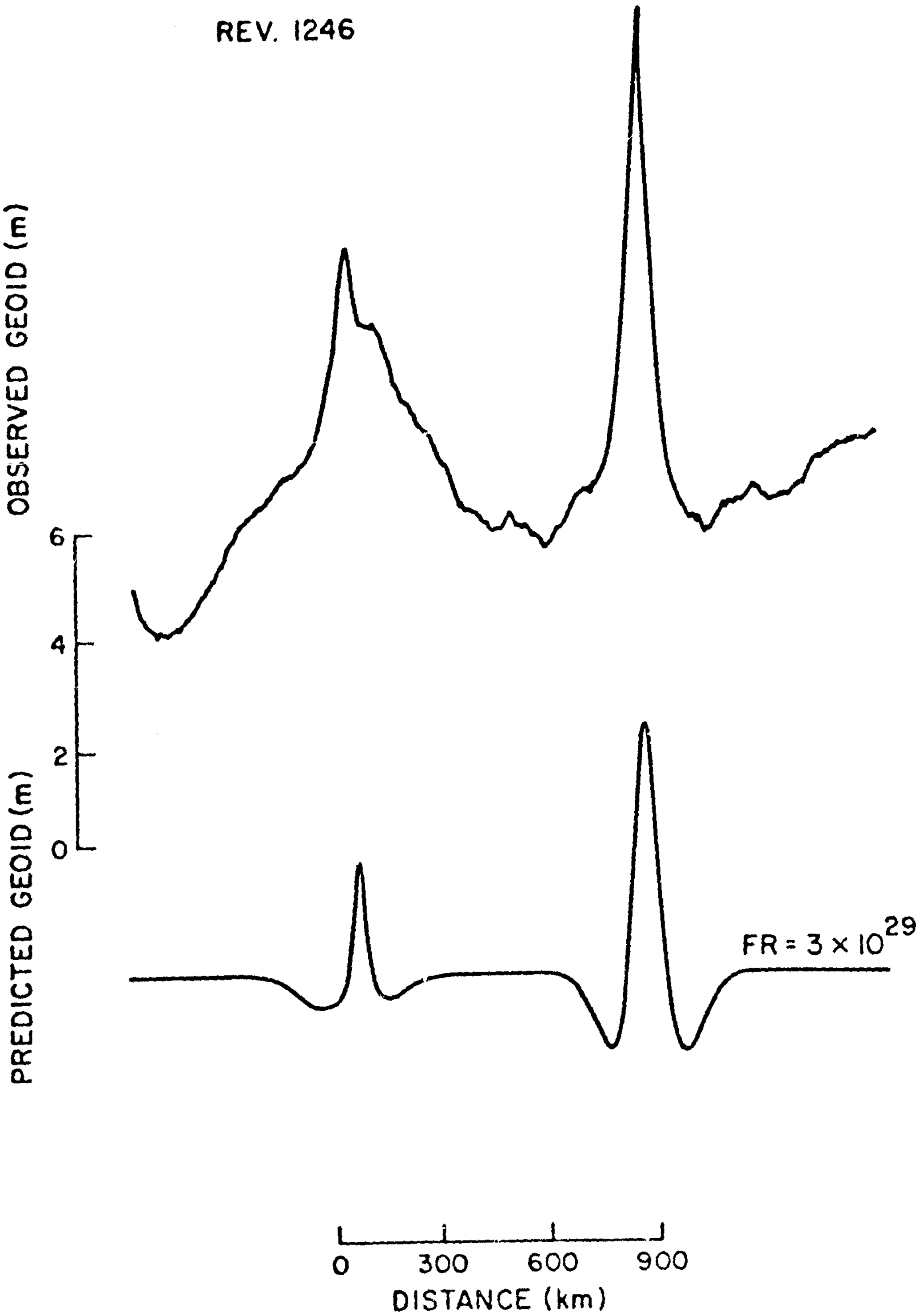

Figure 3. The top profile represents the observed residual geoid heights for the Seasat revolution number 1246 over the New England seamounts. The bottom profile represents the predicted geoid heights calculated with a value for the flexural rigidity of 3×10^{29} dyne-cm.